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Volume V

ICAM MANUFACTURING COST/DESIGN GUIDE

Volume V - Machining

BATTELLE COLUMBUS LABORATORIES
505 KING AVENUE
COLUMBUS, OHIO 43201-2693

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The "Manufacturing Cost/Design Guide" (MC/DG) enables airframe and electronic designers to achieve lowest cost by conducting trade-offs between manufacturing cost and other design factors. The MC/DG permits airframe designers, at all levels of the design process, to quickly compare costs of manufacturing processes and conduct structural performance/cost trade-offs on airframe components and subassemblies in metallic and composite materials.

This phase of the MC/DG program was to develop a functional section of the MC/DG for machining of metals. This section contains cost-driver formats on material hardness and metal removal rates. The cost-estimating data formats provide information on the machining features of frames, wing skins, ribs, stiffeners, etc., machining features of bolts, bushings, etc.; and also general machining features applicable to most machined airframe parts.

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The MC/DG section for machining is intended to be inserted in the three ring binder of the User's Manual for Airframes, UM 450261000, Volume III.

FOREWORD

This "Manufacturing Cost/Design Guide" (MC/DG) section covers work performed on machined metallic parts under Air Force Contract F33615-79-C-5102 from 1 September 1983 - 30 September 1984. The contract is sponsored by the Computer Integrated Manufacturing Branch, Materials Laboratory, Air Force Wright Aeronautical Laboratories. During the period of technical performance, the Air Force Project Manager was Capt. Richard R. Preston. The present Project Manager is Lt. Kenneth A. Lillie.

Battelle's Columbus Laboratories (BCL) is the prime contractor. Mr. Bryan R. Noton is the BCL Program Manager. The subcontractor for development of the MC/DG Machining Section was Metcut Research Associates, Inc., Cincinnati, Ohio. The key personnel on this project at Metcut Research Associates, Inc., were:

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- T. Raj Aggarwal
- Brian E. Barkocy
- Susan M. Harvey.

Support personnel included:

- John F. Kahles
- John B. Kohls
- Alan F. Ackenhauser
- John D. Christopher.

The following consultants participated in this phase of the program:

- Ralph A. Anderson
- Leonard I. MacDonald.

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SECTION 4
MANUFACTURING COST/DESIGN GUIDE DATA SECTIONS

4.10 Machining Section

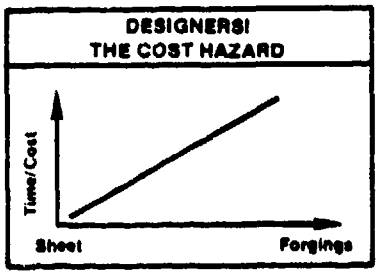
This section offers guidance to designers on difficult machining operations and cost trends, presents MC/DG format selection aids and examples of how the machining data can be utilized in airframe design, and includes a set of MC/DG formats for machining. The formats are of four types: cost-driver effects (CDE), cost-estimating data (CED), designer-influenced cost elements (DICE), and non-recurring costs (NRC).

Machining universally results in the conversion of metal (or other solid material) to chips, shavings, etc. Costs arise from the labor involved in producing, monitoring, or controlling this conversion. Typical material utilization factors for various forms of the starting material are shown in Table 4.10-1 below.

TABLE 4.10-1

MATERIAL UTILIZATION FACTORS:

ALUMINUM



Material Form	Material Utilization Factor
Formed Sheet and Plate	1.7 - 2.2
Chem Milled Sheet and Plate	2.5 - 2.8
Machined Plate	4 - 12
Machined Bar and Rod	4 - 7.5
Machined Forgings*	
5° Die	3 - 6
Blocker	5 - 8
Precision	1.2 - 1.8

*Titanium forgings are approximately 1.0 higher than aluminum forgings.

The type of metallic material selected by designers is normally determined by design requirements, such as static and fatigue properties, corrosion requirements, and available space for the parts in assembly. The designer can seldom tradeoff material costs when selecting a particular metal alloy to meet the complex design requirements. However, the cost-drivers or DICE in machining the part may be favorably influenced. The most significant cost-drivers with machining are:

- Material type and heat-treat range
- Volume of material removed
- Surface finish requirements
- Dimensional tolerances.

These are not the only cost-drivers. A study of large and small airframe machined components revealed that many other cost-drivers are common to the majority of parts. Examples are:

- Starting material form (plate, bar, or forging)
- Part size
- Depth-of-cut to end-mill-diameter ratio
- Thin webs/ribs/flanges
- Corner radii/chamfers
- Tapered lineal sections with multiple breaks
- Ramp transition between web thickness
- Pads (boxes)
- Scalloping
- Spot facing
- Blind holes
- Deep pockets
- Slots
- Special tooling requirements
- Mismatch allowance.

In order to illustrate the complexity factor in cost, General Dynamics Corporation, Fort Worth Division, selected a simple, average, and complex part for the F-16 from each of three machining areas of the plant. These machining areas represented lathes, mills, and profilers. The following piecharts (Figures 4.10-1 to 4.10-3) show the frequency of machining by type of operation, the distribution among machine types by labor man-hours, and the percentage of parts by machine type. This information is included through the courtesy of General Dynamics Corporation.

A single part can be produced on a variety of machines. Hand-operated machines, numerically controlled machines, and machining centers are all applicable for certain parts. Furthermore, cutting tools, cutting fluids, speeds, feeds, depths of cut, work-holding devices, and effectiveness of supporting services are important factors in determining costs.

Primarily, the formats developed provide primarily information on machining run-time. However, data are also included on setup, tooling requirements, and lot sizes.

4.10.1 Format Selection Aids

The Format Selection Aids provide the user with a building-block approach that guides format usage to avoid machining cost-drivers and enables man-hours or cost data to be retrieved for alternative designs. The designer reviews the format selection trees and identifies those areas that impact the design. The formats provide cost-driver effects (CDE) for qualitative guidance to lowest cost and cost-estimating data (CED) in man-hours or dollars.

4.10.2 Building Block Decisions Utilizing MC/DG

Because machining is a process and not an entity, such as a forging, a casting, or a sheet metal part, each design consists primarily of a series of designer-influenced cost elements (DICE). The various formats for these DICE provide qualitative guidance and also man-hours and dollars. Examples of DICE are:

- Taper
- Pockets
- Blind holes
- Webs/flanges
- Tolerances
- Surface finish.

Therefore, an objective has been to provide data on machining for use in the other MC/DG sections on specific discrete parts and thus enable designers to conduct the required structural performance/manufacturing cost trade-off studies.

FIGURE 4.10-1

FTR450261000
6 Mar 1985

FREQUENCY OF MACHINING BY TYPE

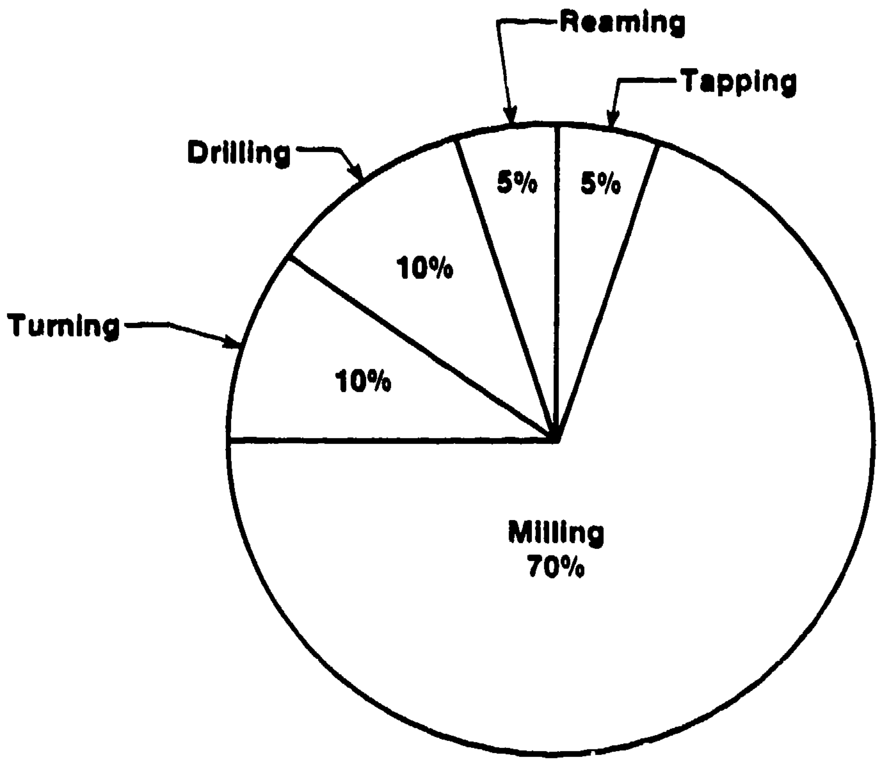


FIGURE 4.10-2

CONVENTIONAL MACHINE SHOP (LABOR)

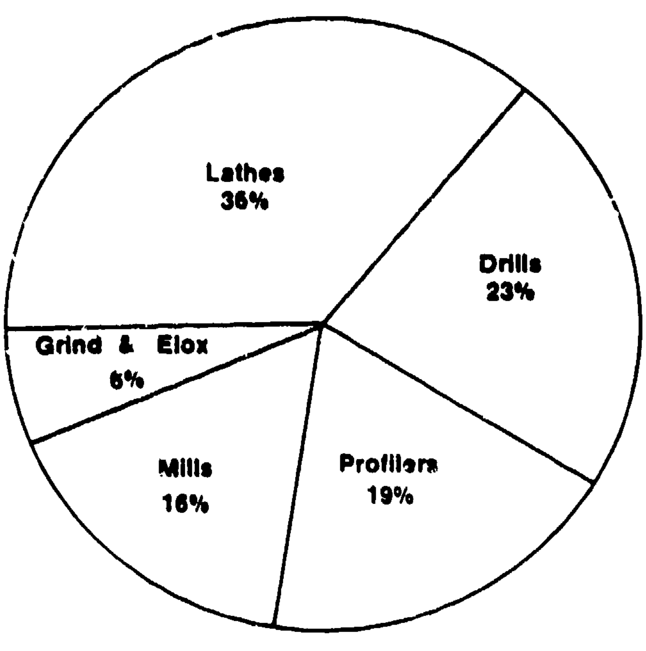
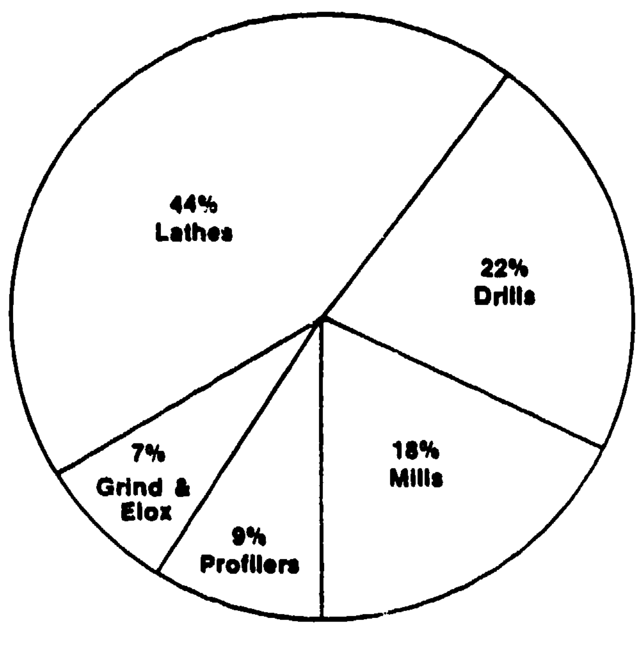


FIGURE 4.10-3

CONVENTIONAL MACHINE SHOP PARTS



Because each machined airframe part is essentially a series of DICE, the designer, utilizing the Format Selection Aids, can identify those DICE of concern and determine the run-time for each element.

4.10.2.1 Use of Learning Curve

The Learning Curve theory, developed from historical manufacturing cost data, is a mathematical means of expressing the reduction in manufacturing labor as an aerospace program proceeds through the production phase. The theory states that "as the production quantity doubles, the labor required to produce a unit is reduced by a constant percentage." For example: For an 80 percent learning curve, the labor required to produce the second unit is 80 percent of that required to produce the first unit; the labor required for the fourth unit is 80 percent of that required for the second unit; etc.

The application of the learning curve varies among companies and the percentage may vary as a program progresses. In the early phases, a 70 percent learning curve may be used with a change to 85 percent learning curve as production continues. Toward the end of the program, labor turnover can result in a man-hour increase, i.e., a negative learning curve.

As shown in Table 4.10-2, the learning curve has a different slope for various manufacturing technologies, such as machining, sheet metal, joining, and bench assembly. The learning curve factor used in cost estimating depends on both the learning curve percentage and the design quantity. Engineering cost analysts in aerospace companies sometimes use the historically determined learning curve percentage for the technology involved and also use, as a design quantity, the number of airplanes to be built, regardless of the number of identical parts per airplane. Occasionally, departmental realization (standard man-hours/actual man-hours) is used instead of the learning curve to analyze costs of high usage operations, such as riveting and nutplate or fastener installation, that are common to many parts/assemblies.

When comparing a proposed design to an existing design in production, reductions in labor that occur during the 'prior production' must be considered, for example:

- Design Quantity : 200 airplanes
- Prior Production: 100 airplanes

The cost analysis would compare the cost of 'existing design' units 101 thru 200 to the cost of the 'proposed design' units 1 thru 100. Table 4.10-3 is included to facilitate this analysis.

TABLE 4.10-2

EXAMPLES OF LEARNING CURVES

Manufacturing Operation	Typical Industry Learning Curve
Machining - Numerical Control	95%
Machining - Conventional	90%
Assembly, Controls	85%
Assembly, Electrical	80%
Assembly, Hydraulics, Pneumatic, etc.	85%
Functional Installation	65%
Plastic Fabrication	85%
Structural Assembly - Bench	85%
Structural Assembly - Floor	75%
Structural Assembly - Final	70%
Sheet Metal Fabrication	90%

NOTE: The above is typical of the aerospace industry and is for use by those designers for whom individual company learning curves are not available.

TABLE 4.10-3

FACTORS TO CONVERT THE MC/DG ONE AND 200TH UNIT COST TO THE CUMULATIVE AVERAGE COST FOR THE DESIGN QUANTITY AND LEARNING CURVE INVOLVED

DESIGN QUANTITY	LEARNING CURVE-%						
	95	90	85	80	75	70	65
1	1.48	2.25	3.48	5.50	9.00	15.00	27.00
10	1.33	1.79	2.47	3.48	5.04	7.53	11.67
25	1.25	1.59	2.05	2.71	3.68	5.13	7.43
50	1.19	1.44	1.79	2.22	2.85	3.76	5.14
100	1.13	1.30	1.52	1.80	2.18	2.73	3.51
200	1.08	1.17	1.30	1.45	1.66	1.95	2.36
350	1.04	1.08	1.14	1.22	1.33	1.48	1.70
500	1.01	1.02	1.05	1.09	1.15	1.24	1.38
750	0.98	0.96	0.96	0.96	0.97	1.01	1.09
1000	0.96	0.92	0.89	0.87	0.87	0.88	0.91

4.10.2.2 Selecting the Learning Curve Factor

Aerospace labor costs are normally collected for cost centers, each representing a different manufacturing technology, and are not traceable to individual parts or assemblies. Labor costs are for a production lot representing a 'mix' of single usage and multiple usage parts/assemblies. From these data, learning curve slopes (percentages) are established for the various cost centers. When estimating the cost of aerospace parts/assemblies, the appropriate learning curve factor is selected by the learning curve percent for the technology involved and the design quantity.

4.10.2.3 Impact of Lot Size

The unit cost of most machined parts is primarily a function of lot size; the larger the lot size, the smaller the impact of "setup" time on the cost of each part. This is illustrated in Figure 4.10-4, which shows that when the lot size for a given part exceeds 25, the impact of setup time is negligible.

As the design engineer has little or no control over lot size or the factors controlling setup time or NRTC's, the major impact of the design engineer on machining cost is on the factors that affect material removal costs or run-time. Furthermore, for the majority of machined airframe parts studied, a large variety of machine types, and therefore setup requirements, could be employed to produce the parts.

EFFECT OF LOT SIZE ON SETUP/RUN-TIME

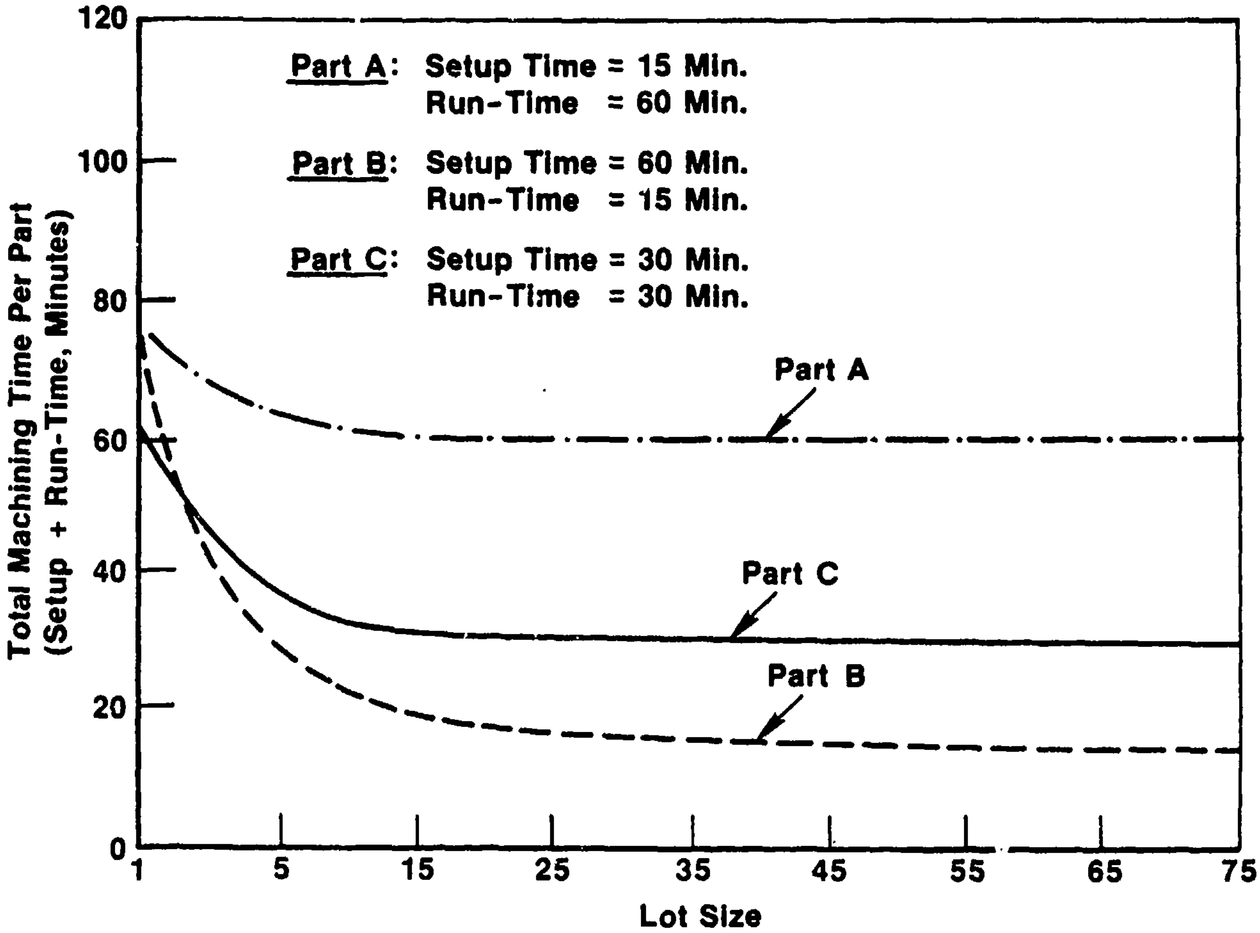


FIGURE 4.10-4. EFFECT OF LOT SIZE ON SETUP/RUN-TIME

4.10.3 Examples of Utilization

This section uses specific examples to demonstrate how the cost data generated for Machining are utilized on a specific design problem. The examples show how to identify applicable formats and extract data from them, and include discussions on how these data are used to determine part costs in man-hours or dollars. The Machining Cost Worksheet can be used to record the cost data for easy reference and use. The following discussion presents guidelines to the five-step approach when using the machining data and formats illustrated in the examples.

4.10.3.1 Generic Guidelines

The MC/DG Machining Section highlights, for designers, the cost drivers that are involved in metal removal. For many airframe parts, selection of a metal alloy is complex. Factors frequently involved in finalizing alloy selection and that may precede cost considerations, include:

- Tensile and compressive strengths
- Bearing strength
- Fatigue performance
- Damage tolerance
- Corrosion avoidance
- Available space for part.

Because frequently, the designer must select an alloy that may have to compete with fiber-reinforced, nonmetallic materials, the selection may not always be based on improved metal removal rates. However, the designer can favorably influence manufacturing cost by specifying designer-influenced cost elements (DICE), such that cost drivers are minimized.

The FIRST STEP in using the data and formats in the Machining Section of the MC/DG is always to review Section 4.10.5: "Cost Hazard Guidance". The designer can readily acquire knowledge, or refresh past experience, on cost drivers in machining of metals and those pertinent to a particular design will be immediately evident. Examples from Section 4.10.5 are:

- Volume of material removed
- Material hardness (metal removal rate)
- Improved surface finish
- Improved tolerances

- Decreasing web thickness
- Increasing rib depth
- Increasing pocket or slot depth.

The SECOND STEP is to review the examples of difficult machining requirements with the metallic airframe part sketches in Section 4.10.4. These airframe part sketches reflect the earlier cost drivers applied to various configurations.

The THIRD STEP is to review the general and detailed ground rules in Section 4.10.9. It is important to determine the scope of the MC/DG Machining Section and its applicability to the problem at hand.

The FOURTH STEP is to review the series of part and other definitions in Section 4.10.11.

The data on the formats for recurring cost are indicated as being for one part, for a unit area, etc. In many cases, a large number of different machines can be used to produce a specific part. Because the designer does not make this decision, the data provided show the run-time in minutes to remove metal. However, formats showing setup time, N/C tape preparation, and proofing provide guidance for interaction with manufacturing concerning the final design.

The FIFTH STEP is to review the Format Selection Aid and certain cost driver effect (CDE) formats. In particular, the designer should study formats CDE-M/C-I & II. The comparative metal removal rates shown, indicate to the designer the relative severity and criticality of the machining cost drivers presented in Section 4.10.5 and also in the CDE and CED formats.

This five-step procedure is generic and should be followed when studying any machined metallic part. Using the engineering sketch or drawing, the design hazards shown in Section 4.10.5, and the Selection Aid, the designer can readily list controllable machining features on the Machining Cost Worksheet. In the case of machining, the majority of these features are DICE. Machining Cost Worksheets can be reproduced from the sample included at the conclusion of the Machining Section.

The three problems that follow demonstrate format utilization.

4.10.3.2 Utilization Examples

I. Problem Statement

Compare the relative cost of three different stringer configurations representative of an aluminum wing panel (see sketches below).

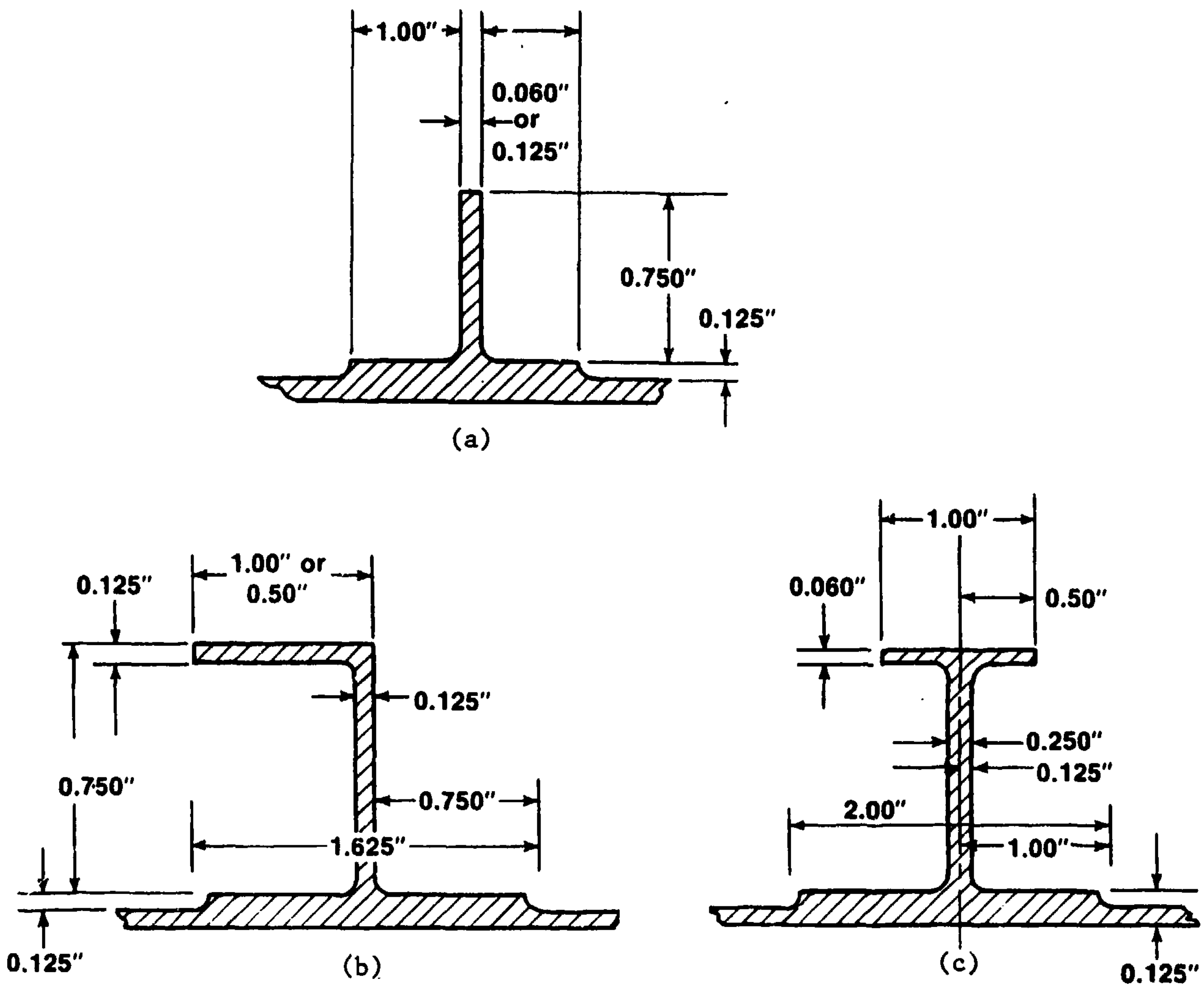


FIGURE 4.10-4. STRINGER/SKIN CONFIGURATIONS

The following procedure is used to determine the machining time for the above parts.

1. Utilize the Format Selection Aid that precedes the formats.

2. Identify the applicable formats, e.g. for plates. In this case, Formats CED-M/C-3 to 5 are required.

3. As aluminum alloy is the material of interest here, the specific format is CED-M/C-3 (Figure 4.10-5).

4. Time to machine the part shown in Figure 4.10-4(a) is:

   2.2 minutes for a 10 inch length.

5. Time to machine the part shown in Figure 4.10-4(b) is:

   3.9 minutes for a 10 inch length.

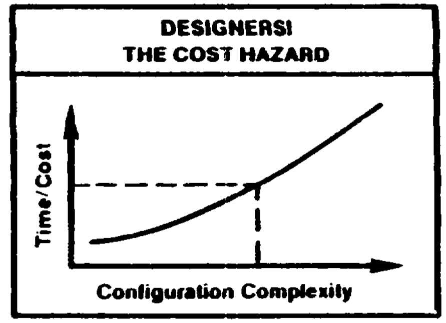
6. Time to machine the part shown in Figure 4.10-4(c) is:

   4.0 minutes for a 10 inch length.

7. Comparing the three configurations, the structural advantage of providing the single or double lips in configurations (b) and (c), respectively, result in an approximately 80 percent increase in cost for machining run time.

To determine the run time for different quantities, the appropriate learning curve for numerically controlled machining can be used, e.g. 95 percent, see Table 4.10-2, in conjunction with Table 4.10-3.

EFFECT OF RIB/STRINGER CONFIGURATION ON MACHINING TIME



ALUMINUM

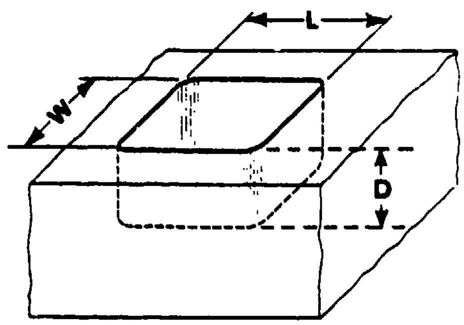
(Sketches of Parts Follow)

Configuration	1 or 2 Thickness of Rib	A or B Height of Rib	X or Y Width of Lip	10°-30°-45° Angle	Time in Minutes to Machine 10" Length
I	-	1.000"	-	-	1.2
	-	3.000"	-	-	3.4
II	0.060"	0.750"	-	-	4.0
		2.000"	-	-	8.0
	0.125"	0.750"	-	-	2.2
		2.000"	-	-	4.0
III	0.060"	1.000"	-	10°	3.4
			-	30°	3.4
			-	45°	3.4
		2.000"	-	10°	7.4
			-	30°	7.4
			-	45°	7.4
	0.125"	1.000"	-	10°	1.6
			-	30°	1.6
			-	45°	1.6
		2.000"	-	10°	3.4
			-	30°	3.4
			-	45°	3.4
IV	0.125"	1.500"	1.000"	-	5.4
				-	5.5
		0.750"	0.500"	-	3.9
				-	3.9
V	0.250"	1.500"	1.000"	-	5.6
		0.750"	1.000"	-	4.0

FIGURE 4.10-5. FORMAT USED IN EXAMPLE I

II. Problem Statement

Determine the machining time for two pockets required in a titanium structural member (see sketch below). The designer may be considering a configuration with a series of pockets.



W = Width
L = Length
D = Depth

Case A: W = ½"; L = 4"; D = 1".

Case B: W = ¼"; L = 8"; D = 1".

FIGURE 4.10-6. POCKET IN TITANIUM PART

Procedure

1. Utilize the Format Selection Aid that precedes the formats. Pockets are a feature required for frames, bulkheads, etc., and this is therefore the group of formats required.

2. In this case, Formats CED-M/C-12 to 15 are required.

3. As titanium is the material of interest here, the specific format required is CED-M/C-13 (Figure 4.10-7).

4. The machining run time for:

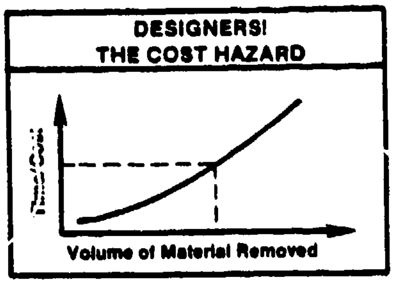
   Case A (2 in^3 removed) = 5 minutes.

   Case B (2 in^3 removed) = 26 minutes.

5. Should the designer require to study the cost impact of additional DICE, such as surface finish and tolerances, the required CED formats can be identified using the Format Selection Aid.

EFFECT OF POCKET/SLOT SIZE AND CONFIGURATION ON MACHINING TIME

TITANIUM



Volume of Pocket/Slot Cu. In.	Dimensions of Pocket/Slot W	L	D
1	1"	1"	1"
	1/2"	2"	1"
	1/4"	4"	1"
	1"	2"	1/2"
	1/2"	4"	1/2"
	1/4"	8"	1/2"
2 Doubling Width	2"	1"	1"
	1"	2"	1"
	1/2"	4"	1"
	2"	2"	1/2"
	1"	4"	1/2"
	1/2"	8"	1/2"
2 Doubling Length	1"	2"	1"
	1/2"	4"	1"
	1/4"	8"	1"
	1"	4"	1/2"
	1/2"	8"	1/2"
	1/4"	16"	1/2"
2 Doubling Depth	1"	1"	2"
	1/2"	2"	2"
	1/4"	4"	2"
	1"	2"	1"
	1/2"	4"	1"
	1/4"	8"	1"
4 Doubling Depth & Length	1"	2"	2"
	1/2"	4"	2"
	1/4"	8"	2"
	1"	4"	1"
	1/2"	8"	1"
	1/4"	16"	1"
4 Doubling Depth & Width	2"	1"	2"
	1"	2"	2"
	1/2"	4"	2"
	2"	2"	1"
	1"	4"	1"
	1/2"	8"	1"
4 Doubling Width & Length	2"	2"	1"
	1"	4"	1"
	1/2"	8"	1"
	2"	4"	1/2"
	1"	8"	1/2"
	1/2"	16"	1/2"
8 Doubling Width, Length & Depth	2"	2"	2"
	1"	4"	2
	1/2"	8"	2"
	2"	4"	1"
	1"	8"	1"
	1/2"	16"	1"

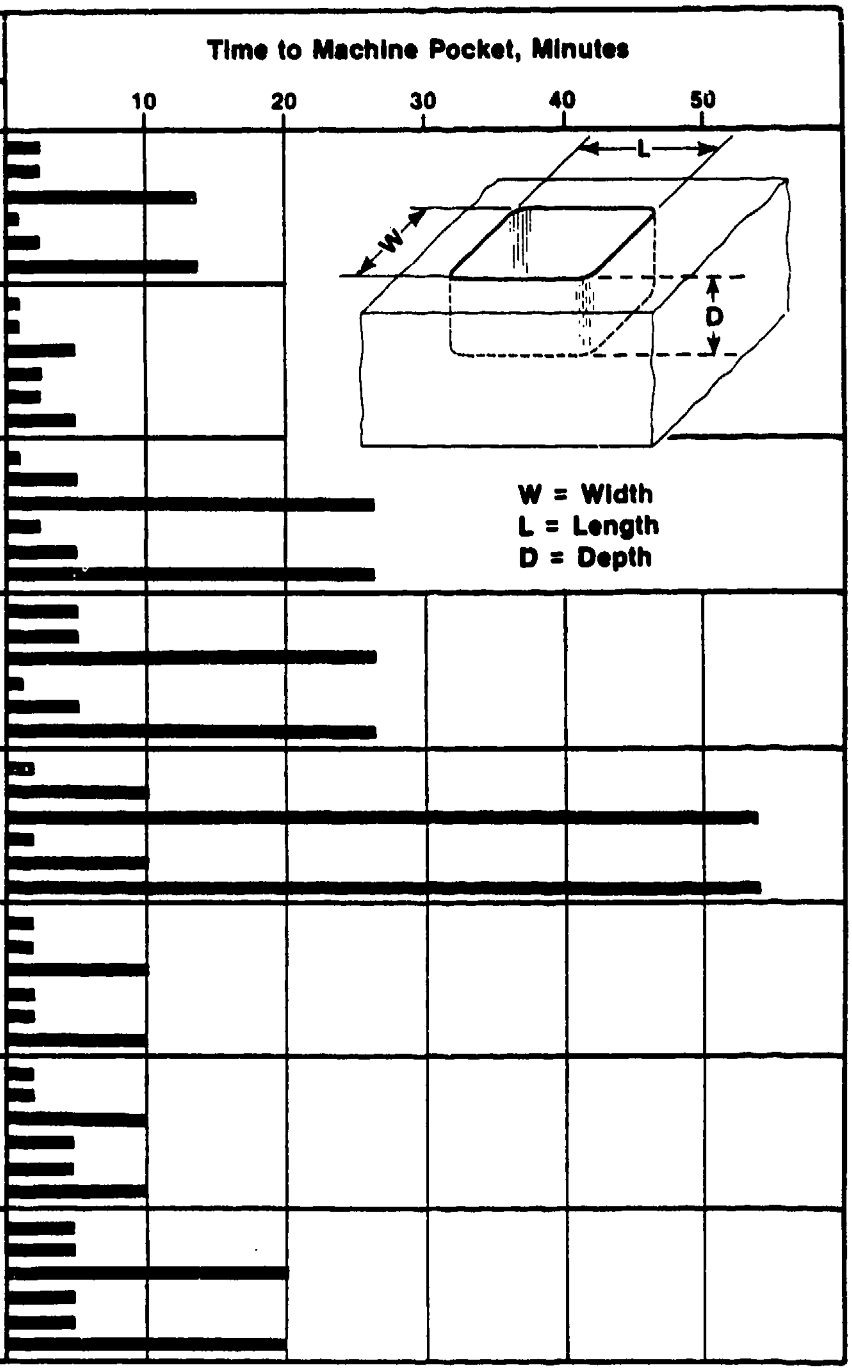


FIGURE 4.10-7. FORMAT USED IN EXAMPLE II

CED-M/C-13

III. Problem Statement

To obtain guidance on depth of a pocket and corner radius selection in an aluminum fitting (see sketch below).

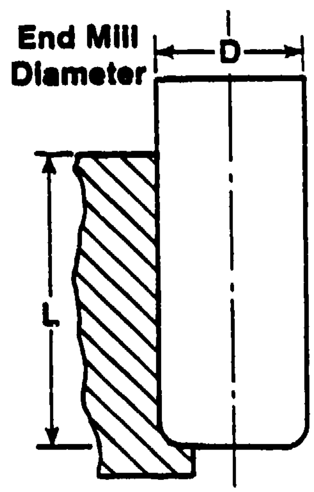


FIGURE 4.10-8. POCKET DEPTH & CORNER RADIUS

Procedure

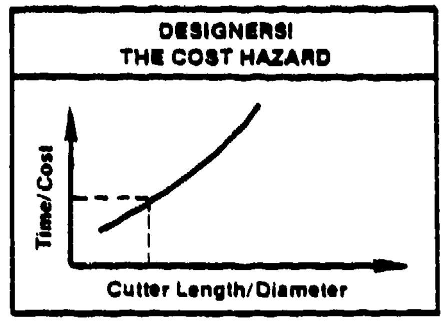
1. Utilize the Format Selection Aid preceding the formats. As cost driver guidance is required, the CDE category of formats is required.

2. For this problem, format CDE-M/C-XV (Figure 4.10-9) is required.

3. The corner radius will, of course, be a function of the overall dimensions of the pocket and the diameter of the cutter. Assuming the pocket size is 4" deep, 6" wide and 12" long, the range of cutter diameter would be 3/4" to 1" providing a 3/8" to 1/2" vertical corner radius. A special cutter can be specified for a similar or smaller base radius.

The final selection of the radii will be determined by structural considerations and also weight saving incentive, e.g. for a subsonic aircraft component the larger radius may be selected, and for a supersonic aircraft, the smaller.

EFFECT OF CUTTER DIAMETER ON MACHINABILITY FACTOR



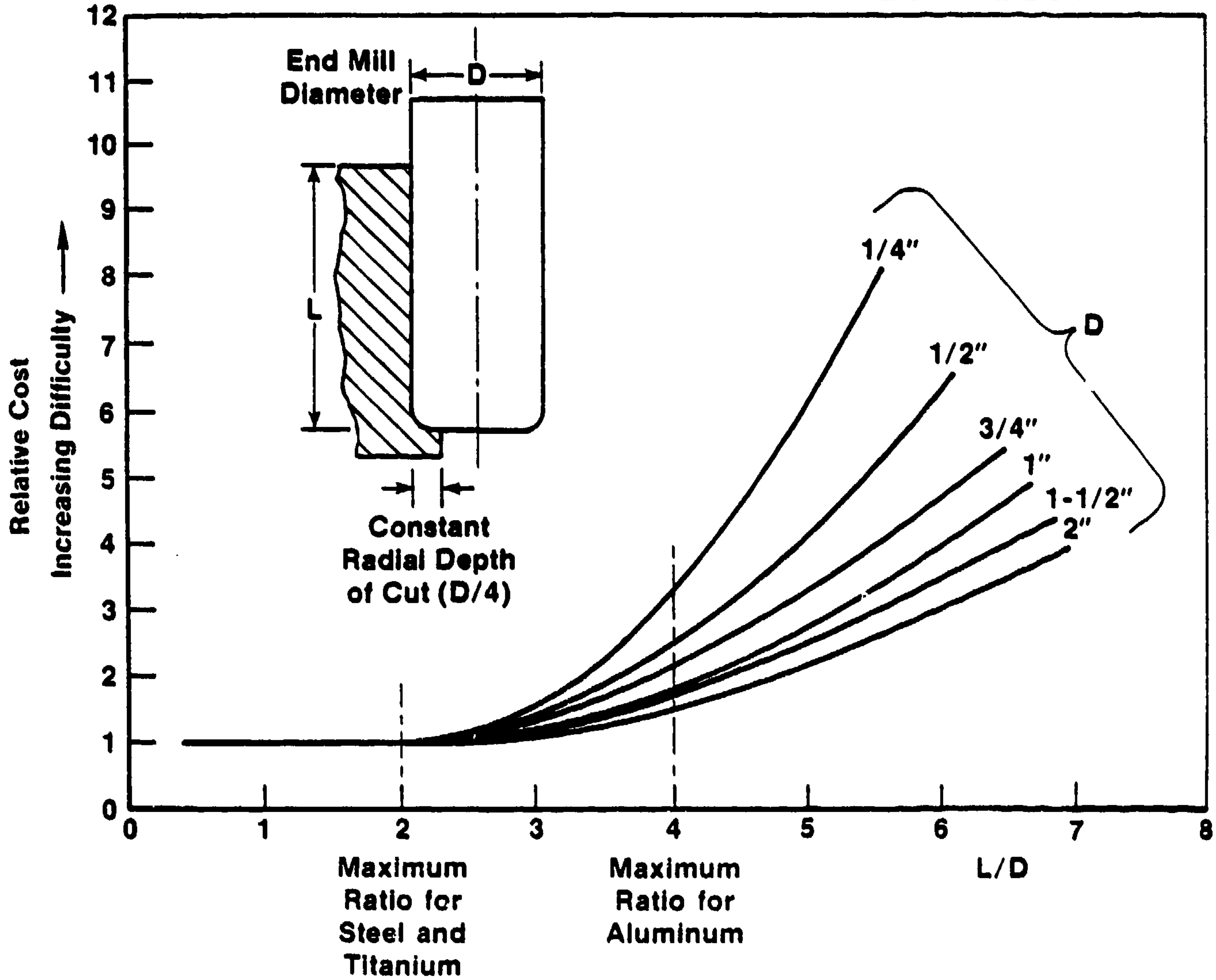
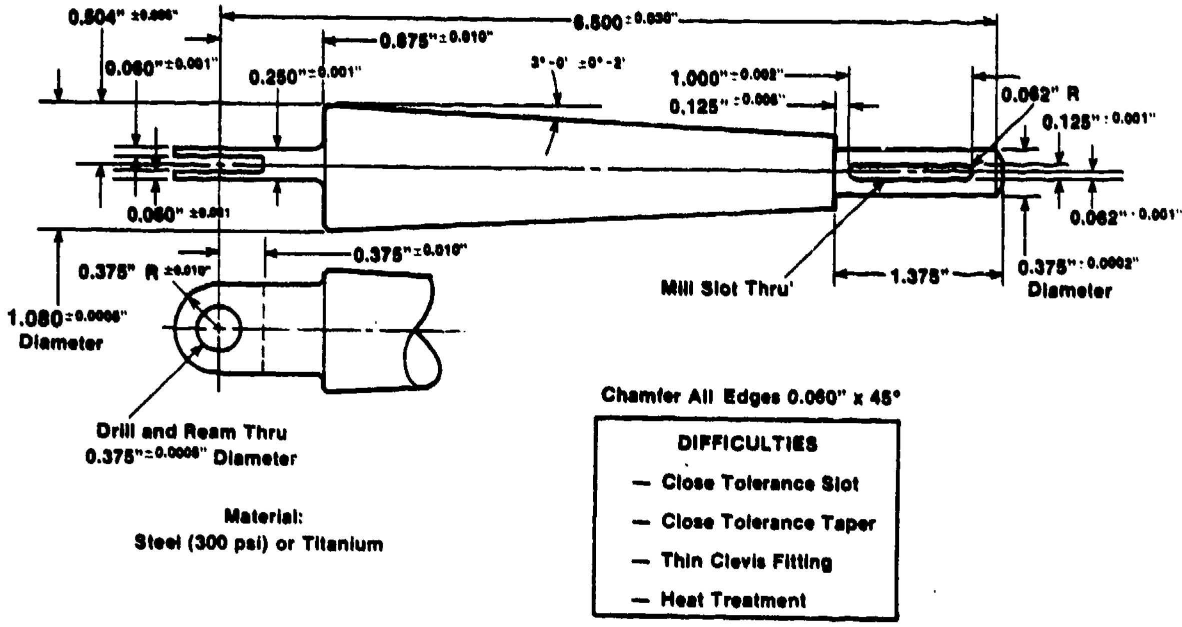


FIGURE 4.10-9. FORMAT USED IN EXAMPLE III

4.10.4 Difficult Machining Requirements

This subsection of the MC/DG Machining Section indicates characteristics of machined parts that cause difficulty in the shop and, hence, increase manufacturing costs. These examples are not exhaustive. Designers may decide to add to this section and, thus, maintain a record of their own experience on cost hazards and cost avoidance with machined parts.

FIGURE 4.10-10. DIFFICULT MACHINING REQUIREMENTS



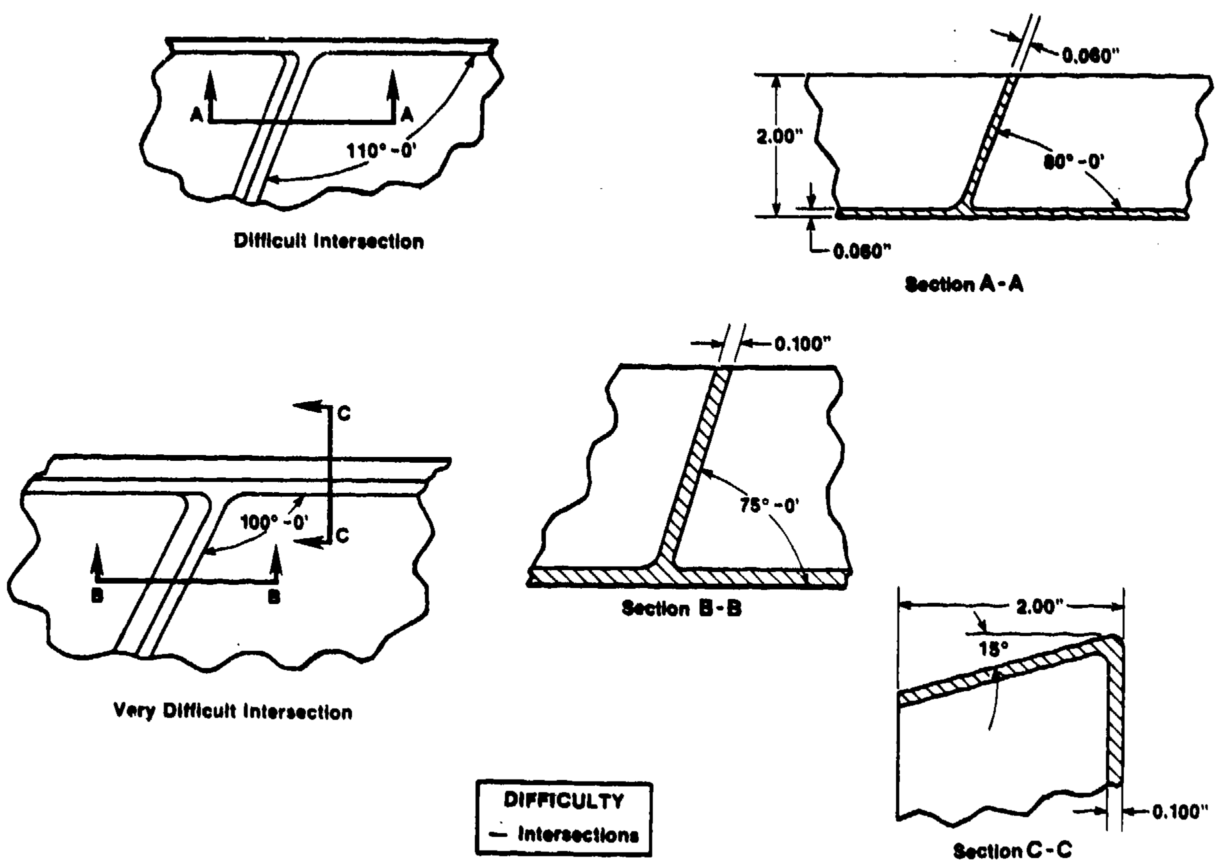


FIGURE 4.10-11. DIFFICULT MACHINING REQUIREMENTS

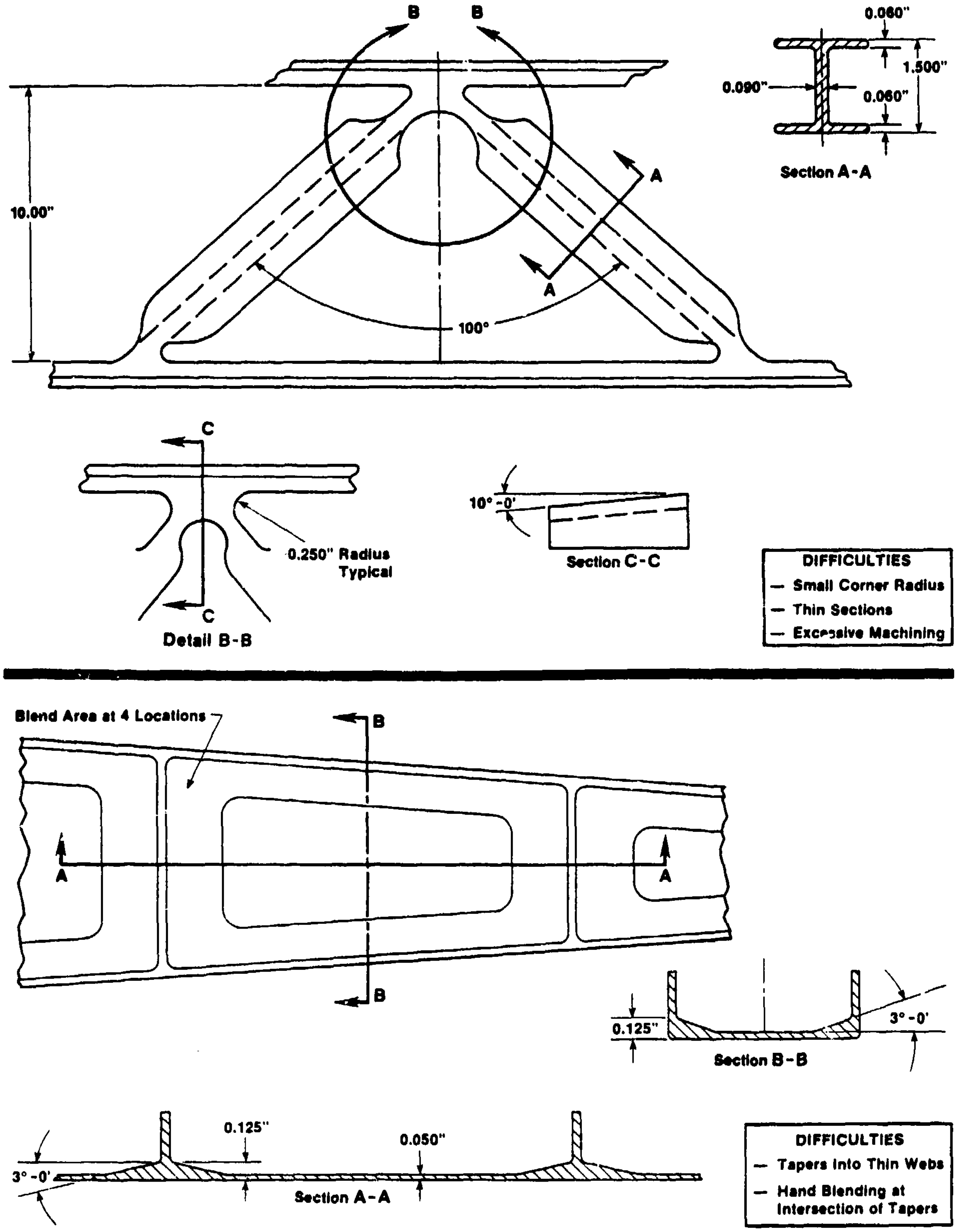


FIGURE 4.10-12. DIFFICULT MACHINING REQUIREMENTS

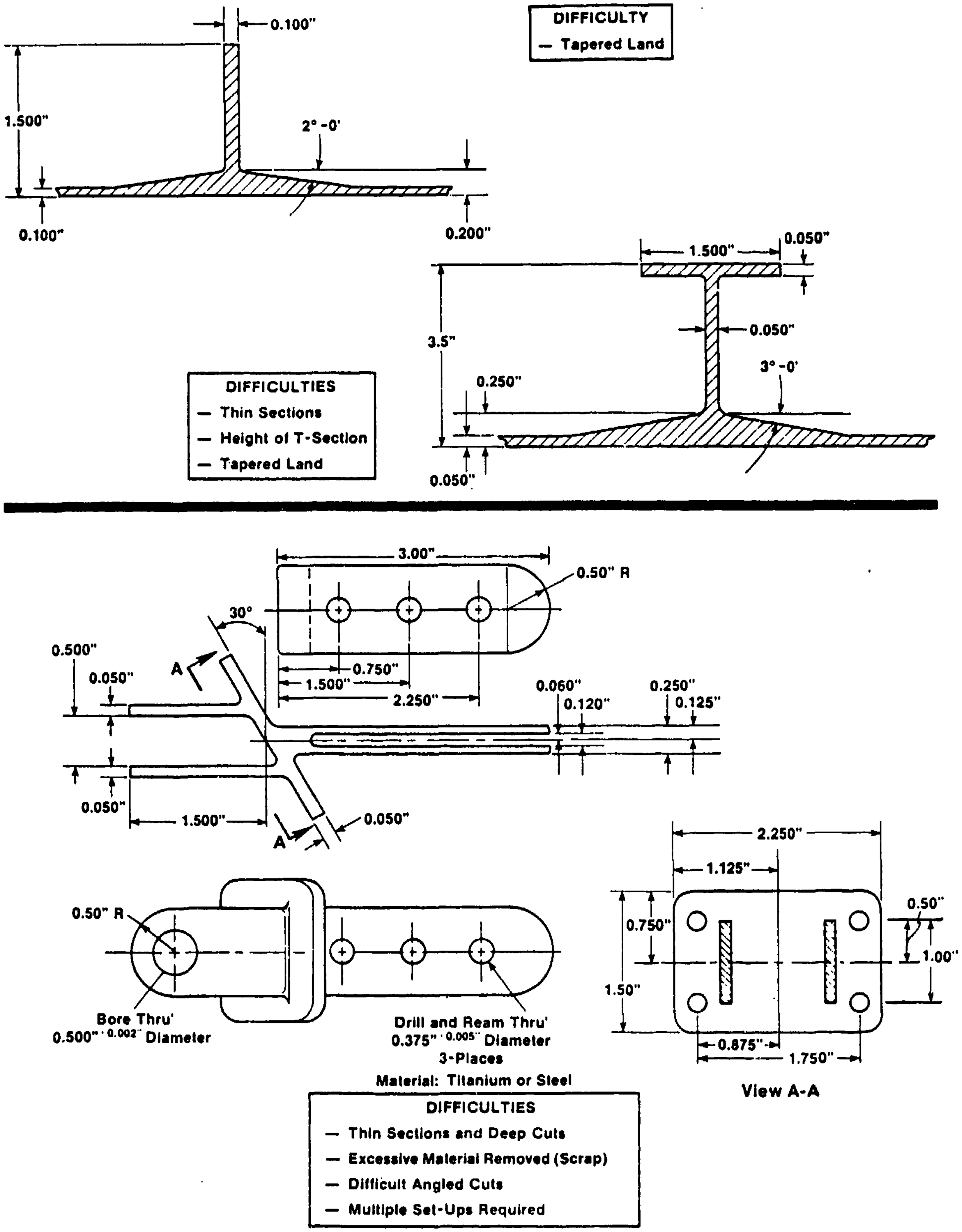
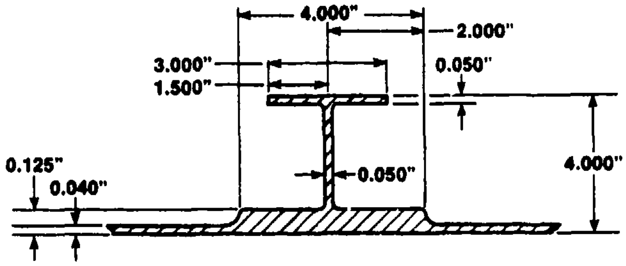
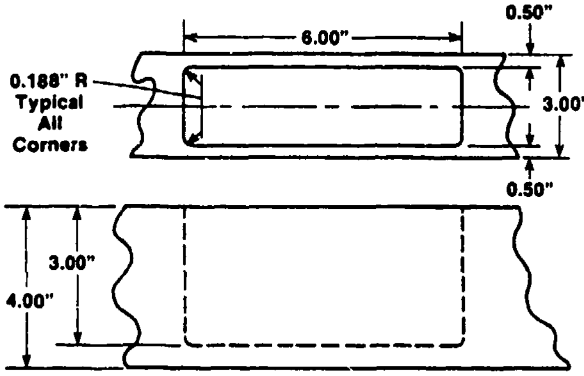


FIGURE 4.10-13. DIFFICULT MACHINING REQUIREMENTS

DIFFICULTIES

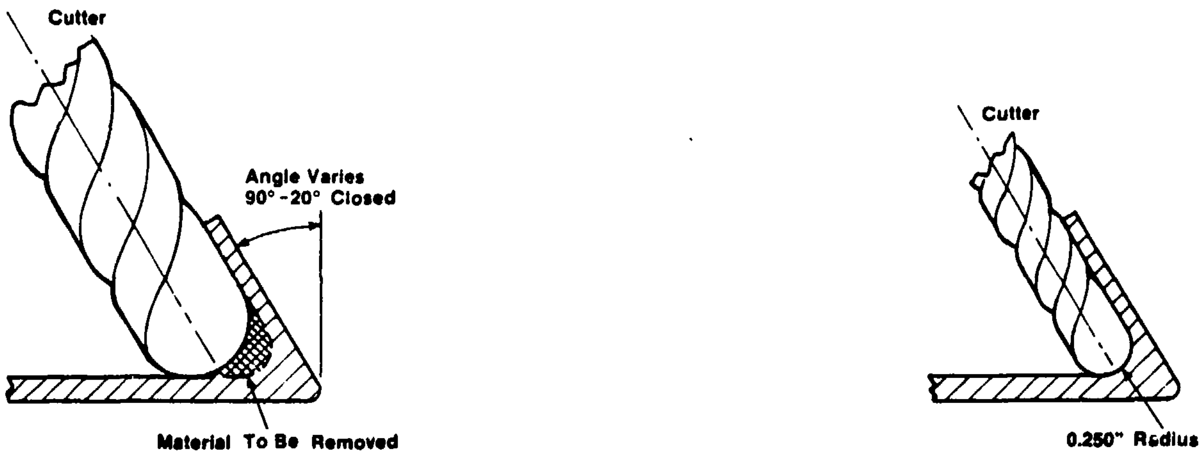
- Very Deep Section With Thin Webs
- Webs Under 0.125" Thick and Over 2.00" Deep Are Cost-Drivers





DIFFICULTIES

- Very Deep Section Requiring 0.375" Diameter Cutter
- Cutters Less Than 0.750" Diameter and Requiring Depth of Cut in Excess of 1.00" Are Cost-Drivers

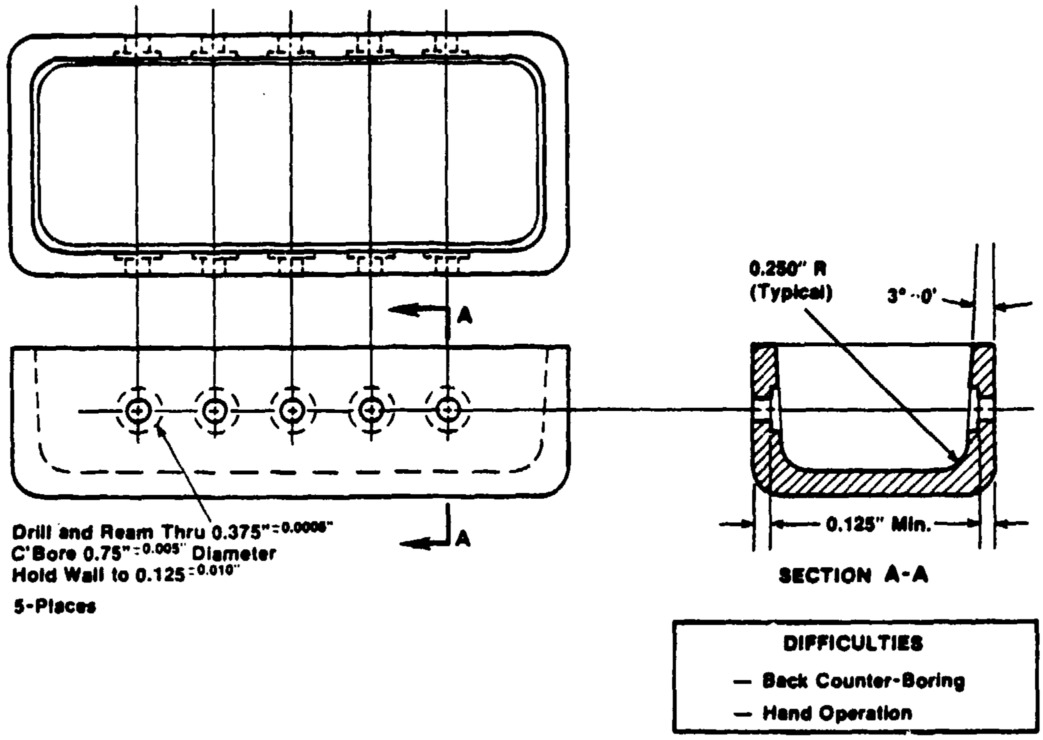


Effect of Closed Varying Angle on Cutter Size

DIFFICULTIES

- Small Secondary Cutter Required to Remove Additional Material
- With Constant Angle, Special Cutter Can Be Utilized

FIGURE 4.10-14. DIFFICULT MACHINING REQUIREMENTS



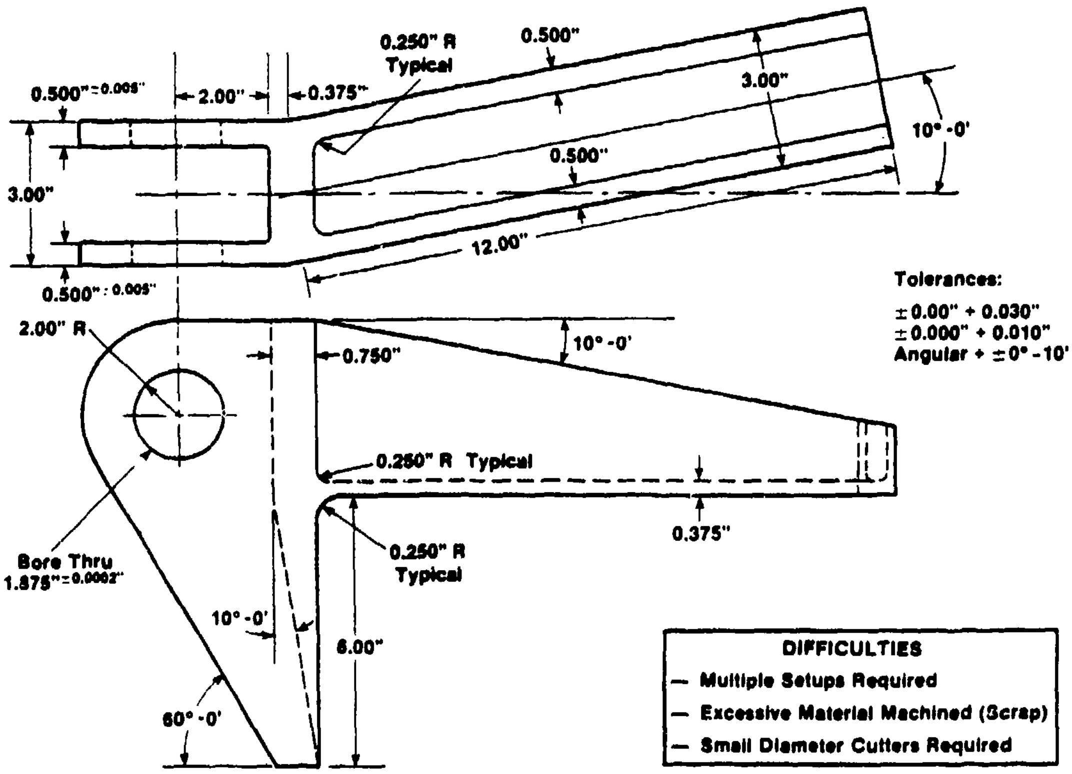
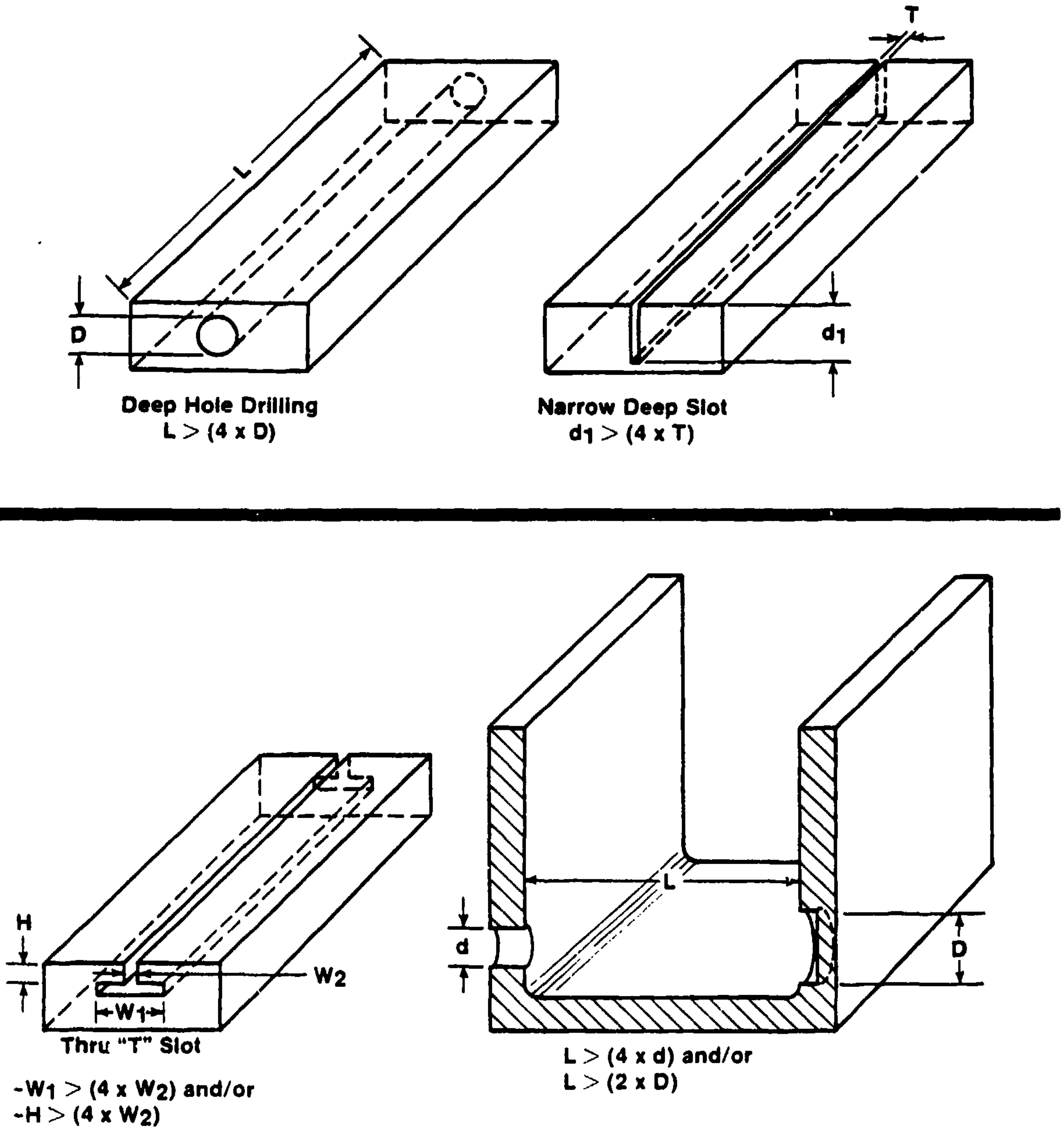


FIGURE 4.10-15. DIFFICULT MACHINING REQUIREMENTS



4.10.5 Cost Hazard Guidance

Each format included in the Machining Section indicates the magnitude (relative or actual) of one or more cost-drivers. Therefore, due to the complexity of the machining process, diagrams that quickly reveal the cost hazard in question were prepared for each format. The increase or decrease of cost, material removal rate, or material utilization is presented as a function of the primary parameter in this diagram. While each of the diagrams appear at appropriate places throughout the Machining Section, they are assembled in this subsection to provide designers, manufacturing, procurement, and management personnel, and the customer with an immediate overview of these cost-drivers, the magnitude of which can then be determined on the format. Such guidance is extremely valuable to inexperienced designers, who may not have shop experience. Furthermore, it promotes, indeed encourages, the design/manufacturing interaction so important in achieving lower cost aerospace systems that perform efficiently throughout their life-cycle.

FIGURE 4.10-16

DESIGNERS!

THE COST HAZARDS

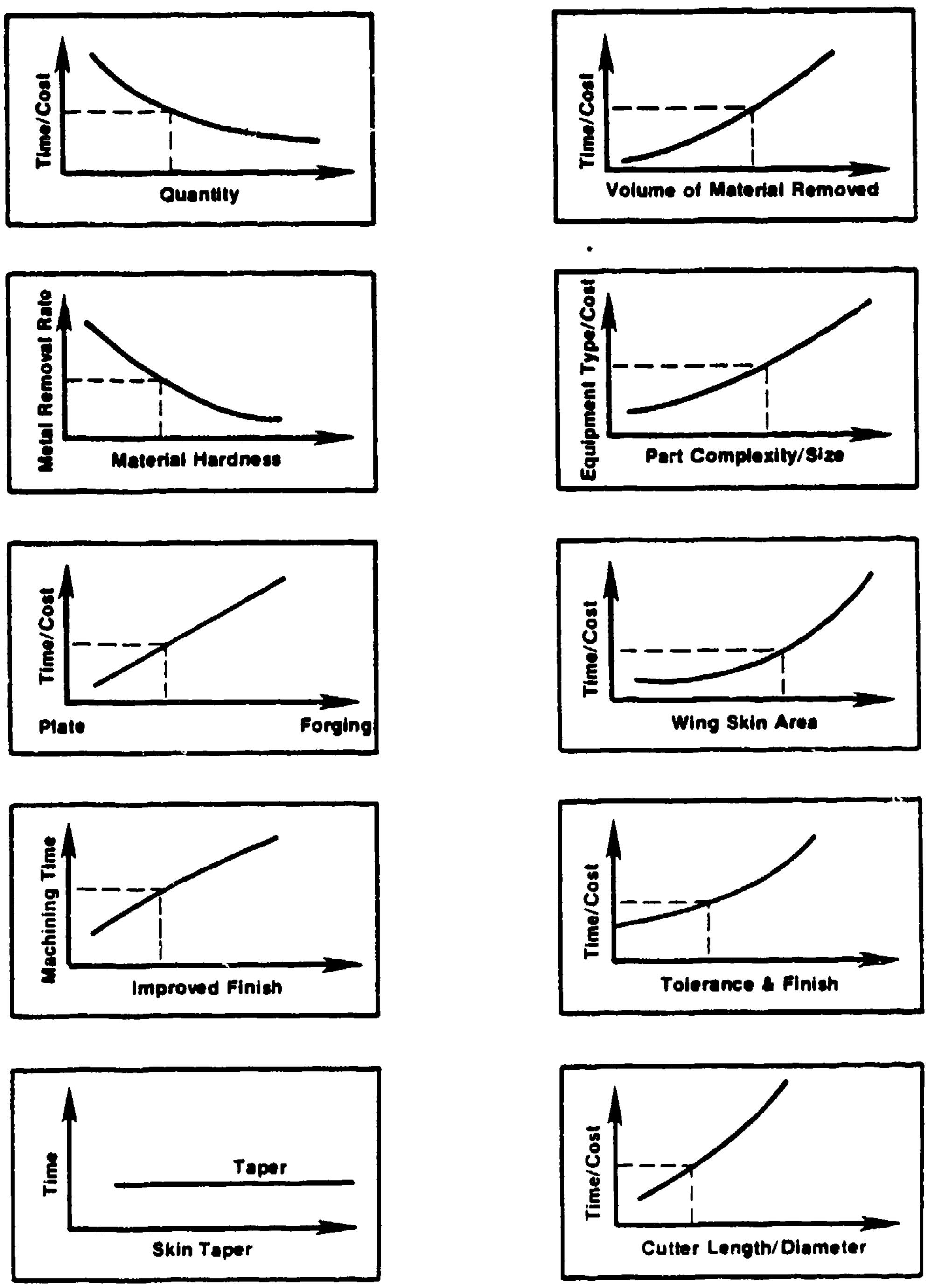


FIGURE 4.10-17

DESIGNERS!

THE COST HAZARDS

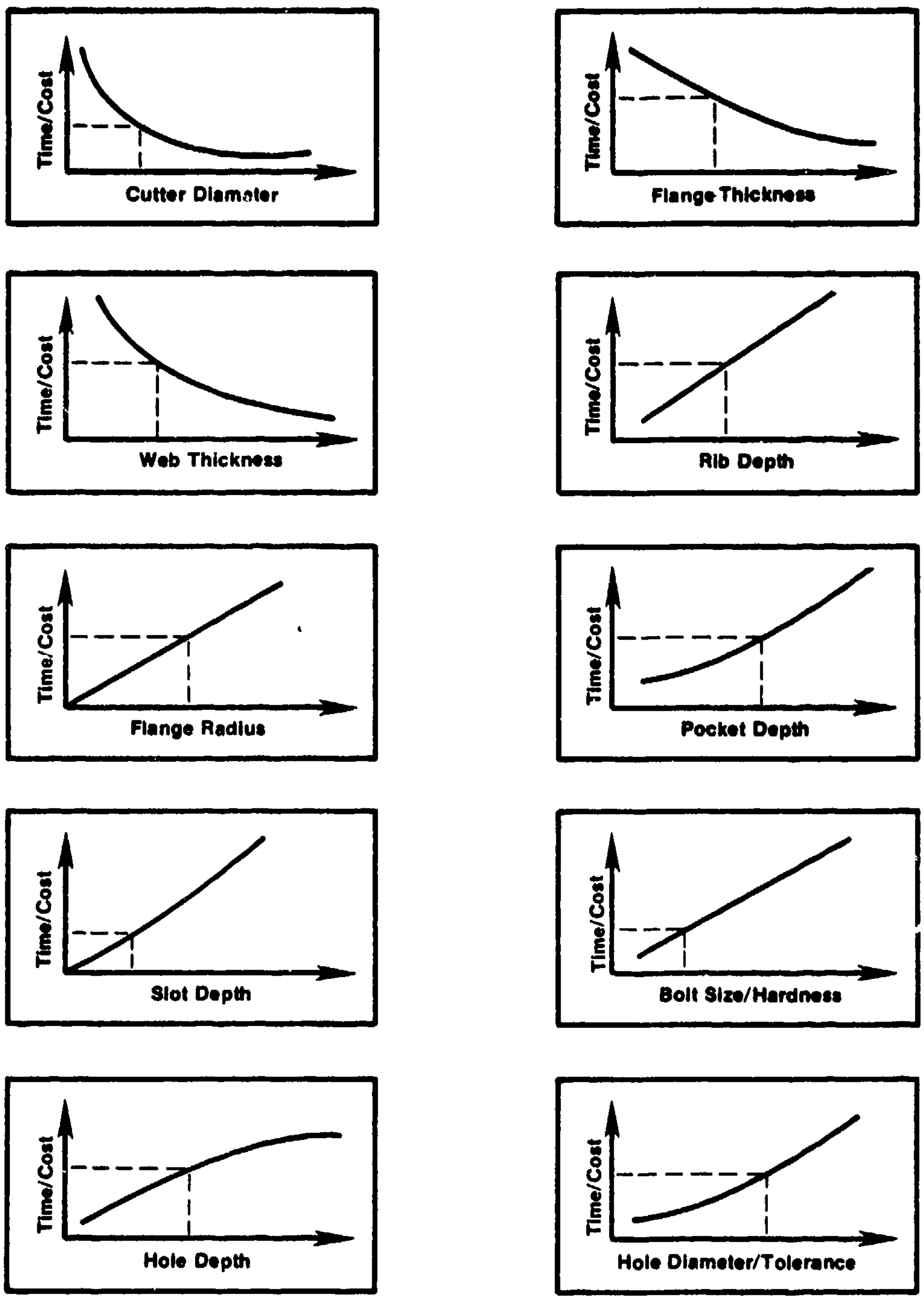
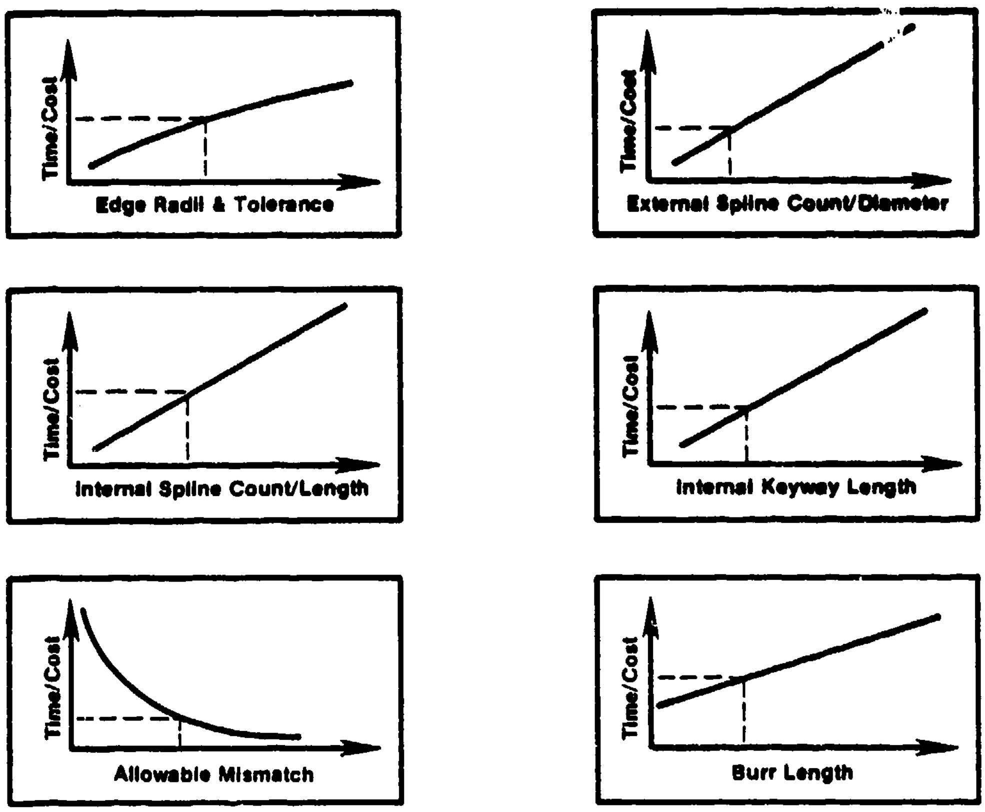


FIGURE 4.10-18

DESIGNERS!

THE COST HAZARDS



4.10.6 Machined Parts Reviewed

The airframe parts reviewed to prepare machining formats included a variety of lineal shapes, surface parts, and small machined parts. Examples in each category are:

Lineal Shapes:

- Beams
- Spar-caps
- Longerons

Surface Parts:

- Frames
- Bulkheads
- Wing-skins

Small Machined Parts:

- Splice "T"
- Apex fitting
- Wing leading-edge fitting
- Wing rib.

The following cost-drivers for these airframe parts are common machining operation requirements. While the listings seem redundant, they emphasize the commonality of cost-drivers.

Cost-Drivers for Bulkheads and Frames:

- Size
- Material removed
- Pockets or slots
- Internal stiffeners
- Varying flange angles
- Boring and drilling of holes
- Varying radii and chamfers

Cost-Drivers for Ribs:

- Size
- Material removed
- Pockets or slots
- Internal stiffeners
- Varying flange angles
- Boring and drilling of holes
- Varying corner radii and chamfers

Cost-Drivers for Spars:

- Size
- Material removed
- Pockets
- Stiffeners
- Varying flange angles
- Boring and drilling of holes
- Varying radii and chamfers

Identification of these cost-drivers enabled part sketches to be prepared to isolate the cost-drivers and to permit the machining run-time to be calculated.

4.10.7 Formats for Machining

The following directions apply to utilizing the formats in this section:

1. Review ground rules in section for considerations and limitations.

2. Refer to the CDE subsection to determine the variation in metal removal rate for different alloys. A large number of aluminum, titanium, and steel alloys are utilized in airframe design. In some cases, these alloys are used primarily in a single company for a single project.

3. Be aware of the range of factors, besides manufacturing cost, that will play an important role in selecting an airframe material. The design requirements may include:

   - Elevated temperatures
   - Fatigue performance
   - Damage tolerance
   - Operation in corrosive environments
   - Ease of repair.

   All factors must be carefully considered by the designer prior to selecting a material or design concept based on manufacturing or acquisition cost. However, higher acquisition costs might be acceptable if lower operations and maintenance costs can be realized.

4. Review definitions in Section 2.2 "Terms and Abbreviations". Important terminology used on most formats in this Machining Section are:

   (a) Designer-Influenced Cost Elements (DICE): Includes pockets, taper, blind holes, special tolerances, and surface finishes that add cost to the part. These additional costs are due to the increased fabrication operations and tooling required over the standard manufacturing method (SMM).

   (b) Detail or Discrete Parts: A distinct machined airframe structural part that incorporates complexities, i.e., DICE, and is ready for assembly to perform its required function in the airframe.

4.10.8 Machining Cost Data

Formats are provided for machining cost data. The data are provided for a series of important DICE that can be utilized for large components, such as wing skins and webs, and also for a series of small parts, such as bushings, bolts, splines, and clevice fittings. Furthermore, formats are included indicating setup and tooling for different equipment. The designer does not control machine tool selection or its operating cost. However, using a series of definitions as the basis and various lot sizes, the relative operating cost for small, medium, and large machine tools with varying numbers of axes is indicated for small, medium, and large parts in accordance with the part complexities defined in subsection 4.10.10.

A survey was conducted of the most commonly used materials on the F-15, F-16, F-18, B-1B, and C-5B aircraft. A large number of aluminum alloys, titanium alloys, and steels are used in these systems. While it is not possible to provide the manufacturing man-hours for each of the alloys identified, CDE formats showing metal removal rates have been prepared for a range of each of these airframe metallic materials.

4.10.8.1 Nonrecurring Tooling Cost (NRTC) and Setup Time

Ground rules for the machining section of the MC/DG define NRTC as tool design man-hours plus the tool manufacturing man-hours required to design and fabricate a specific tool. Under these ground rules, numerical control tapes are considered NRTCs. However, "perishable" or "consummable" tools, such as mill cutters, drills, and reamers, were to be considered standard and not NRTCs.

Although the time required for metal removal (run time/chip cutting time) will be very comparable for a specific part when the configuration, material, etc. are known, both the setup time and NRTCs can vary considerably.

Tool selection and the method of fabrication are based on the design engineer's drawings and specifications. The best judgment of the tool/production planner on the most economical method of fabrication is based on the following criteria:

- Type of equipment available
- Total number of parts to be fabricated
- Lot sizes
- N/C vs. conventional tooling
- Part configuration
  - complexity
  - size
  - material
  - design specification
  - design specification constraints
  - processing requirements
- Schedule requirements

Although the actual NRTCs and setup time depend primarily on the fabrication method determined by the tool/production planner, the design engineer, by using the formats provided, can arrive at reasonable man-hour estimates of both NRTCs and setup time for a given part. On the majority of parts with a production run or total quantity exceeding 200, the NRTCs are a relatively small part of the total cost. Run time and setup time are recurring costs and are the major elements in the total cost. However, the setup time per part depends on the number of parts in the lot size, and the complexity of the setup or type of machine can vary from a very small part of the recurring costs to a fairly substantial part.

Formats

The formats provided for NRTC represent the most commonly used tooling for machined parts. Project/contract tooling can be defined by three basic classifications:

Simple - Small holding fixtures for milling, lathe work, drilling, reaming, and tapping; flat, one surface profile templates, etc.

Average - Medium sized holding fixtures for milling or positioning parts, profiling models, drill jigs for more than one surface and multiple hole patterns, etc.

Complex - Generally those that are too heavy to be lifted or positioned without a hoist. They may be large vaccuum type chucks, large drill jigs, mill fixtures, etc.

Numerically Controlled Tapes

Simple - N/C drill press, N/C lathe.

Average - NC/machining centers, medium-sized N/C profile type parts.

Complex - Complexed large parts on N/C skin mills or large N/C profile machines.

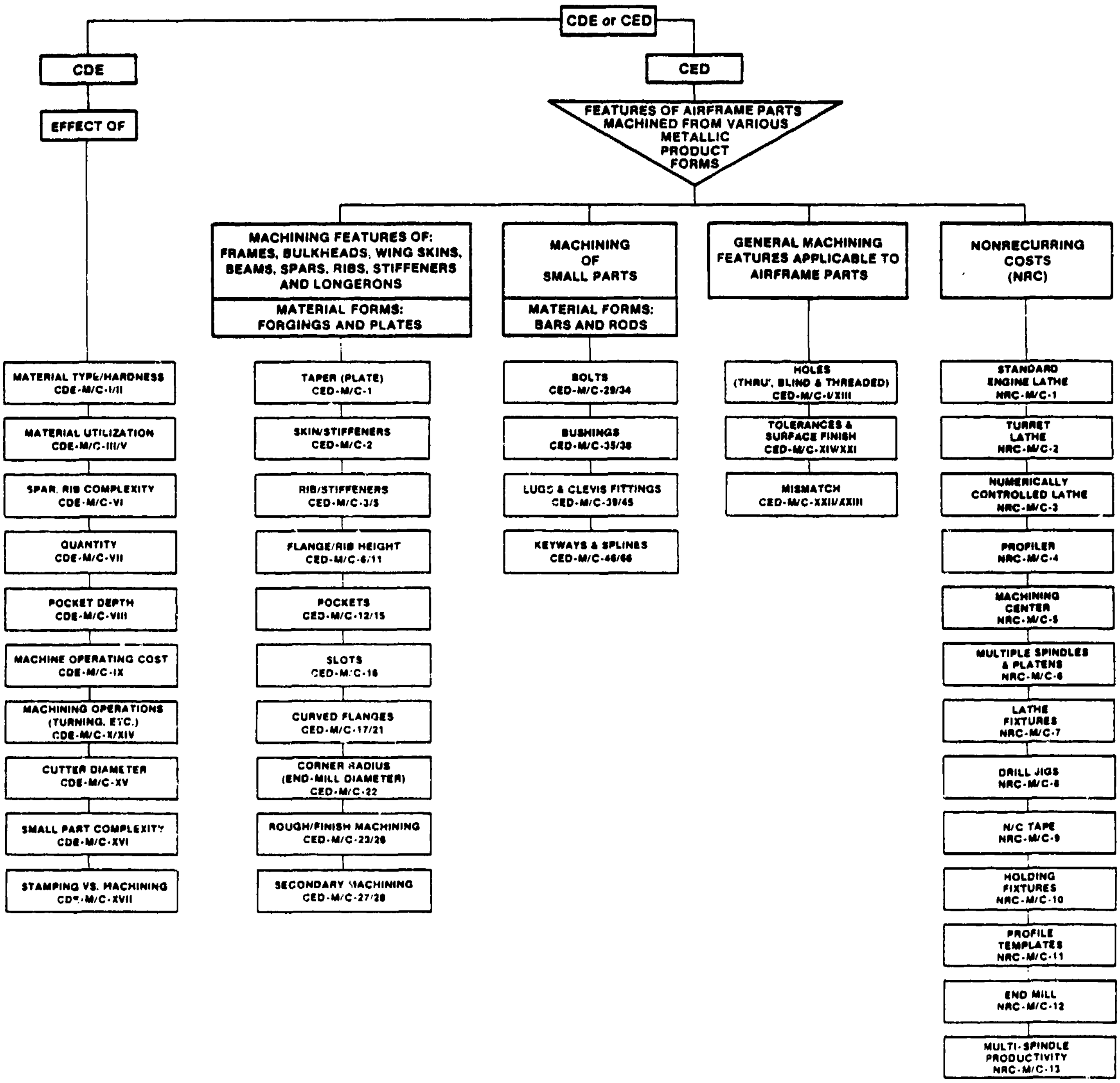
4.10.8.2 Formats for Setup Time

The formats for setup time are, in general, industry standards for the more commonly used machines in the aerospace industry. They do not include time expended by the machine operator in obtaining tooling or material, which is handled differently by different aerospace companies. The setup time can be greatly reduced by some of the more recent developments with complete machining centers, where most of the loading, unloading, and moving of parts is accomplished by automation or semi-robots, etc., utilizing pallets, etc., to setup and move fixtures and tooling. The setup time in this type of advanced manufacturing will include the total setup time for the full complement of machines. This type of semi-automation has not been evaluated. However, for the run time, the formats developed will be applicable to this type of manufacturing technology.

4.10.8 Machining Cost Data

FORMAT SELECTION AID

MACHINING OF METALS



FORMAT SELECTION AID

MACHINING OF METALS

CDE

MATERIAL TYPE/HARDNESS
CDE-M/C-I/II

MATERIAL UTILIZATION
CDE-M/C-III/V

SPAR, RIB COMPLEXITY
CDE-M/C-VI

QUANTITY
CDE-M/C-VII

POCKET DEPTH
CDE-M/C-VIII

MACHINE OPERATING COST
CDE-M/C-IX

MACHINING OPERATIONS
(TURNING, ETC.)
CDE-M/C-X/XIV

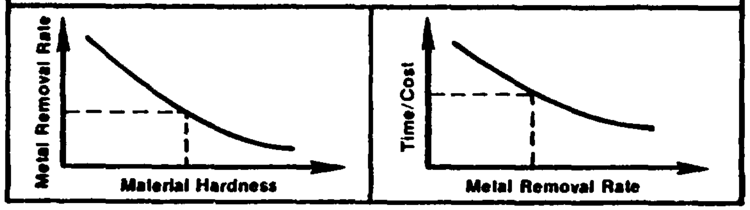
CUTTER DIAMETER
CDE-M/C-XV

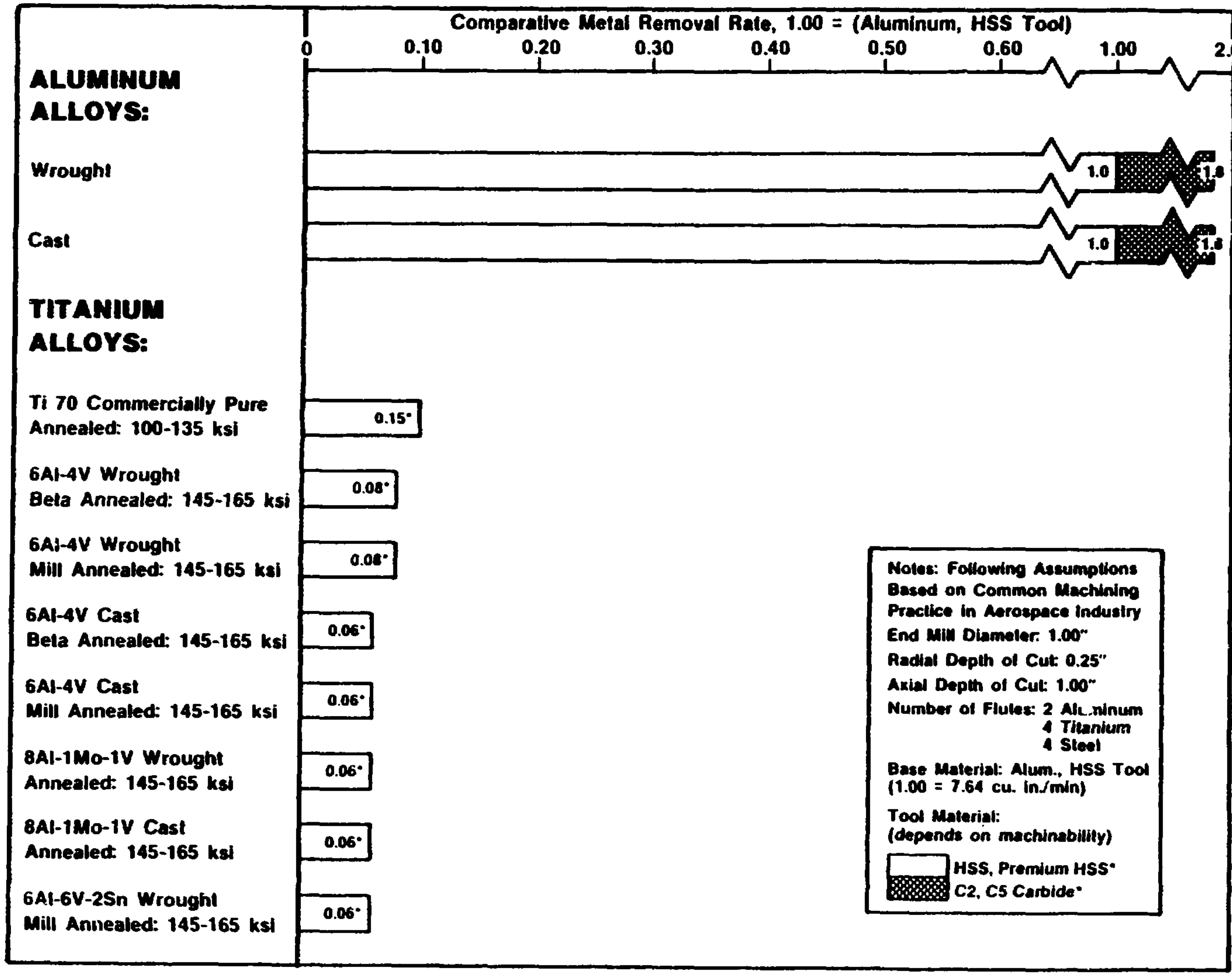
SMALL PART COMPLEXITY
CDE-M/C-XVI

STAMPING VS. MACHINING
CDE-M/C-XVII

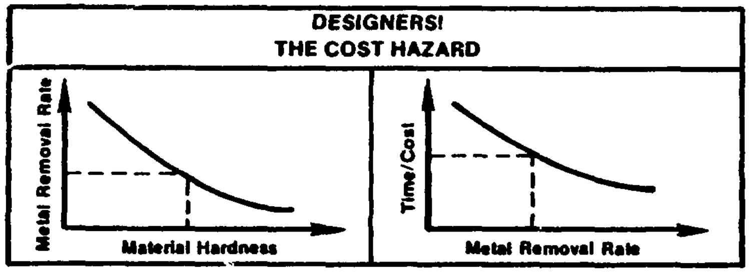
COMPARATIVE METAL REMOVAL RATES
(Peripheral End Milling)

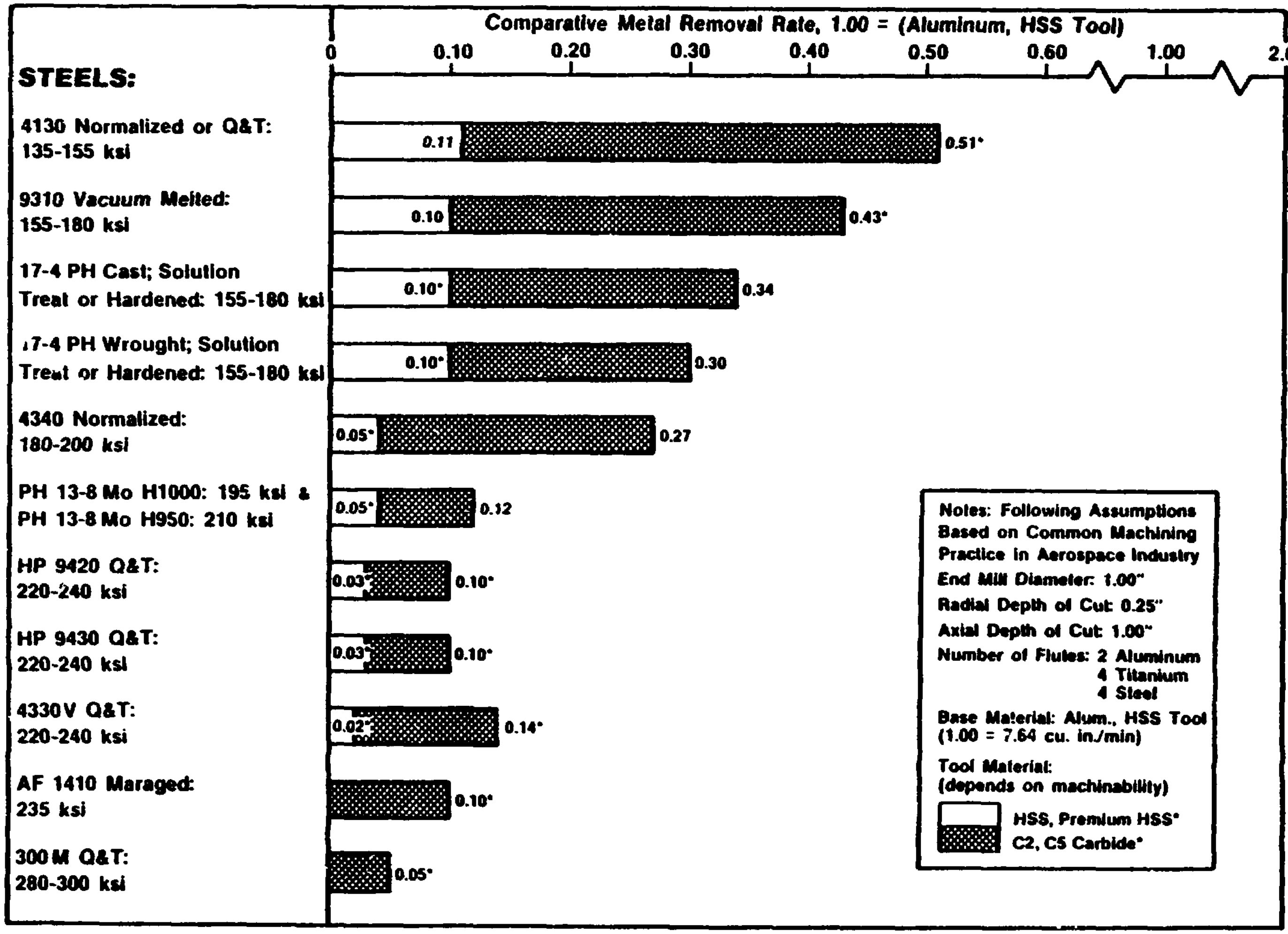
DESIGNERS!
THE COST HAZARD



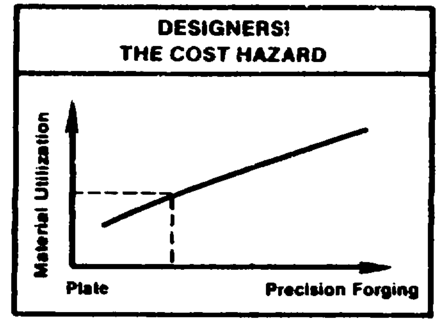


COMPARATIVE METAL REMOVAL RATES (Peripheral End Milling)

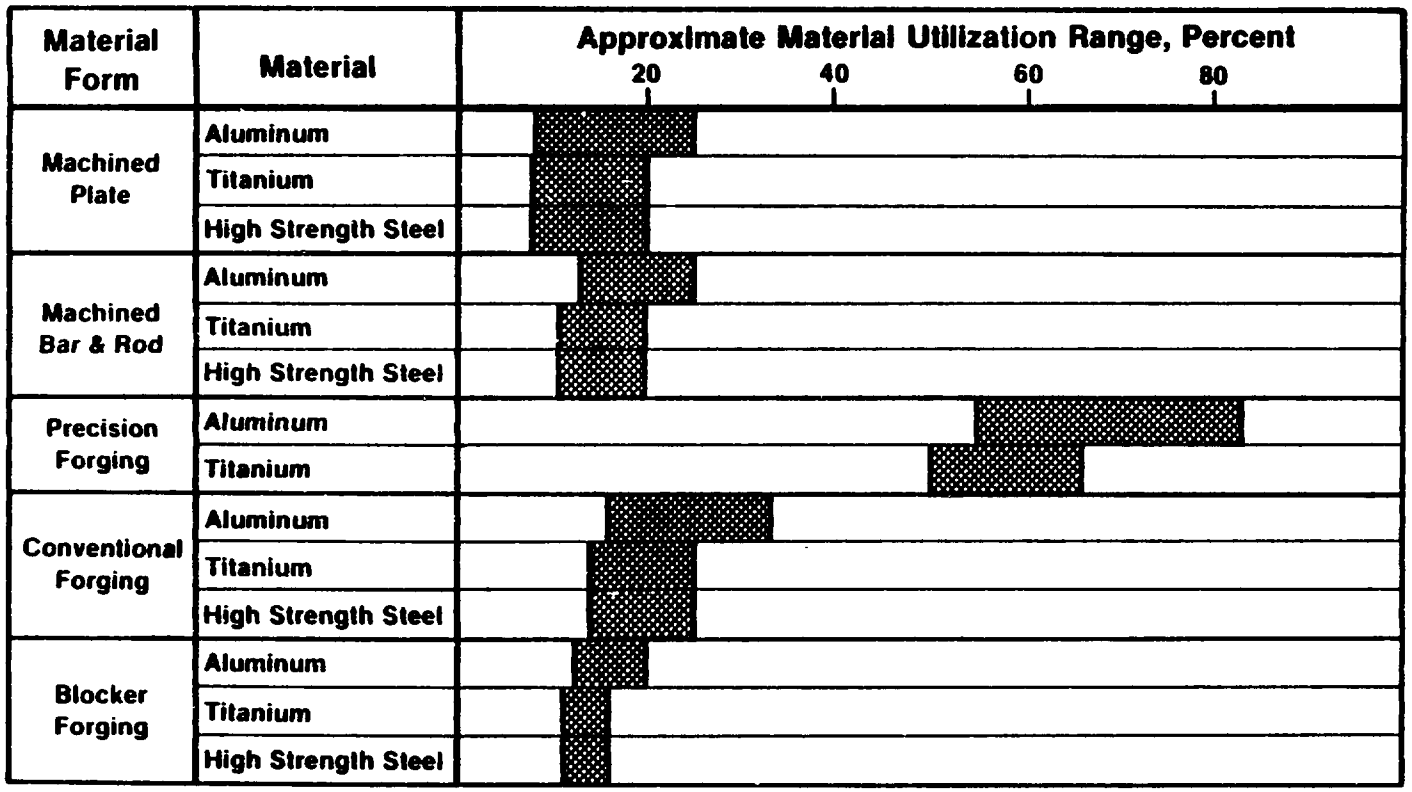




EXAMPLES OF MATERIAL UTILIZATION FOR VARIOUS FORMS: PLATE, BAR, ROD AND FORGINGS



(Excludes Drilling Holes, etc.)



METAL REMOVAL RATIOS FOR TITANIUM BARS AND RODS GENERALLY APPLICABLE TO:

ALUMINUM AND STEEL

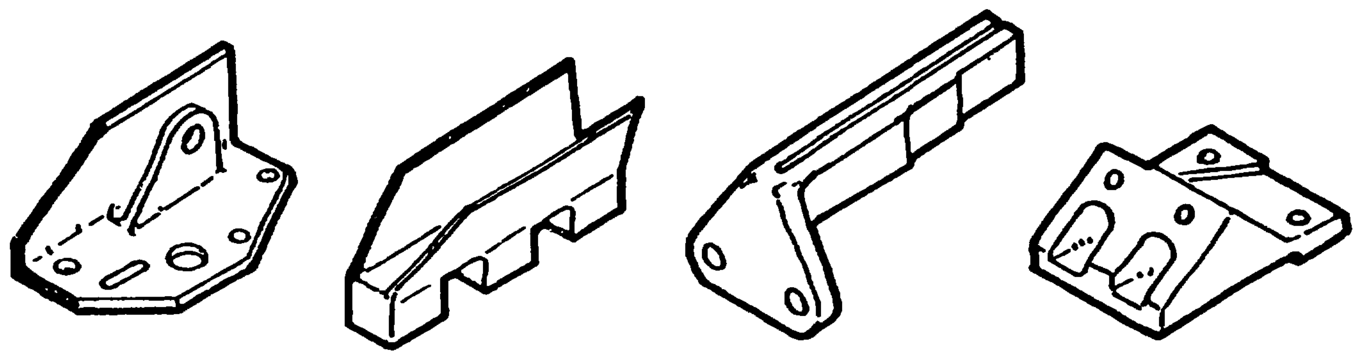
Principal Structural Applications:

Shafts, Tracks, Latches and Small Parts Where Material Grain Flow Does Not Justify Forged Part.

Metal Removal Operations:

Milling, Boring, Sawing, Drilling

Typical Machined Parts Made From Bar



Bar Stock	56 oz.	46 oz.	88 oz.	15 oz.
Finished Part	5 oz.	5 oz.	11 oz.	4 oz.
Metal Removal Ratio	11.2:1	9.2:1	8.0:1	3.7:1

Average Metal Removal Ratio with Allowance for Parts not so Severely Machined—6.9:1

Courtesy of Lockheed-California Company

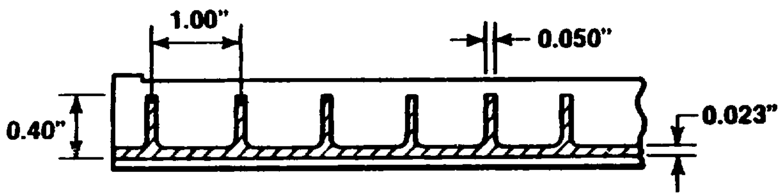
METAL REMOVAL RATIOS FOR TITANIUM PLATE GENERALLY APPLICABLE TO: ALUMINUM AND STEEL

Principal Structural Applications:

Secondary Wing Structure, Leading and Trailing Edge Integrally-Stiffened Skins

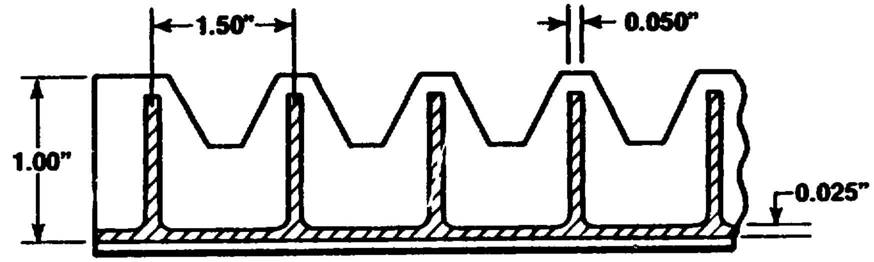
Metal Removal Operations: Milling, Boring, Sawing

Possible Alternative Configurations:



Typical Cross Section Machined from Flat Plate

Metal Removal Ratio - 12:1



Typical Cross Section Machined from Rolled Section

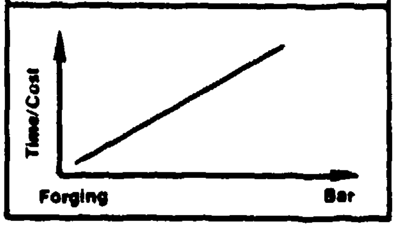
Metal Removal Ratio - 15:1

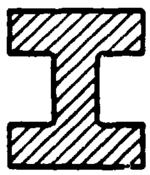
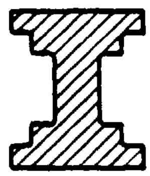
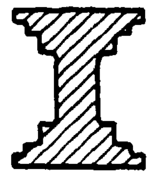
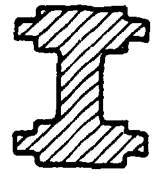
Average Metal Removal Ratio with Allowance for Scallop, Machine Grip and Trim - 14.5:1

Courtesy of Lockheed-California Company

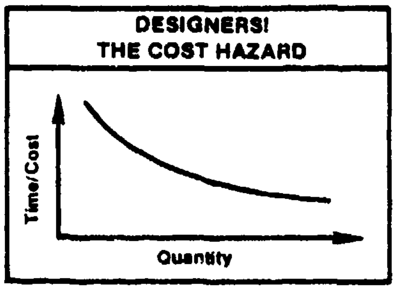
EFFECT OF FLANGE/ATTACHMENT CONFIGURATION FOR SPARS, RIBS, ETC.

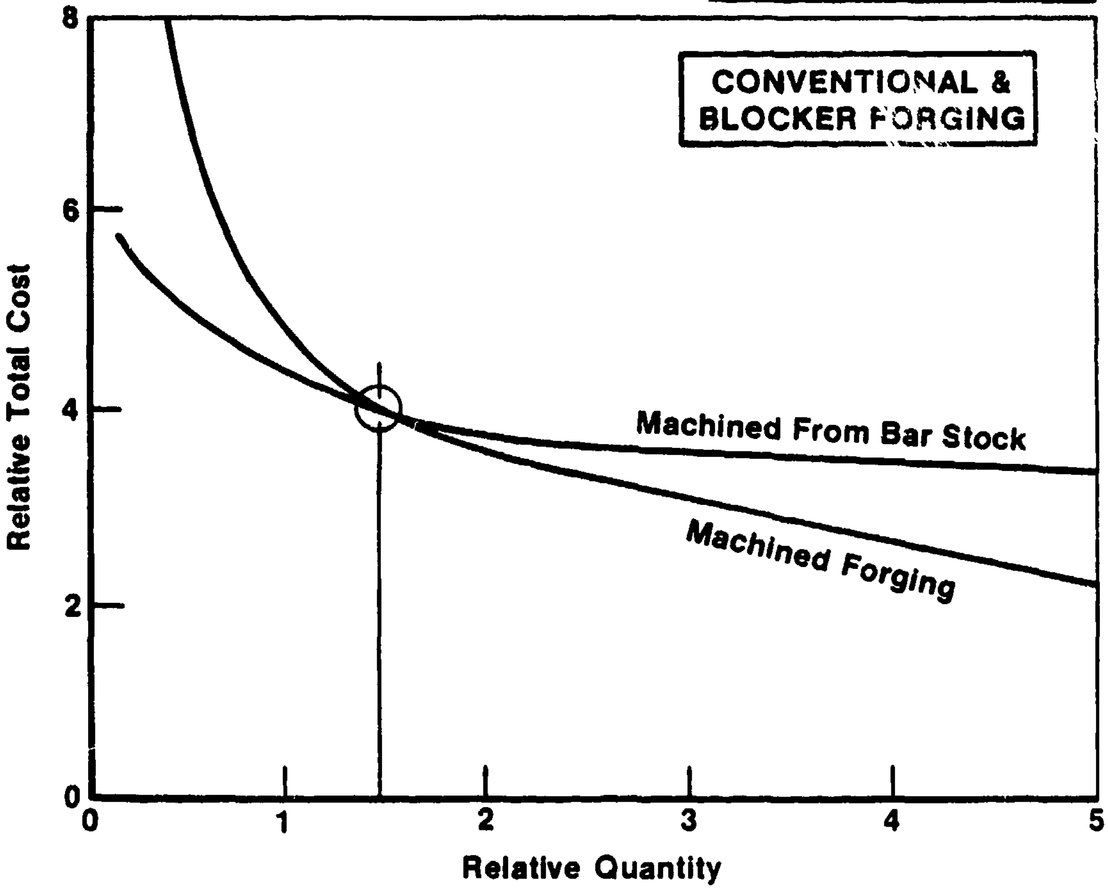
DESIGNERS!
THE COST HAZARD



		Relative Machining Time			
Raw Material Form	Material				
Aluminum	Bar Stock	1	1.1	1.3	1.5
	Extrusion	0.4	0.6	0.8	0.9
	Close Tolerance Forging	0.5	0.6	0.8	0.9
Titanium	Bar Stock	9.5	9.5	12.5	13.0
	Extrusion	4.0	5.5	8.0	9.0
	Close Tolerance Forging	4.0	5.5	8.0	9.0
4340 Steel (Normalized)	Bar Stock	7.0	7.5	9.5	10.5
	Extrusion	3.0	4.5	6.0	6.5
	Close Tolerance Forging	3.0	4.5	6.0	6.5

RELATIVE TOTAL COST OF PARTS MACHINED FROM FORGINGS AND BAR STOCK

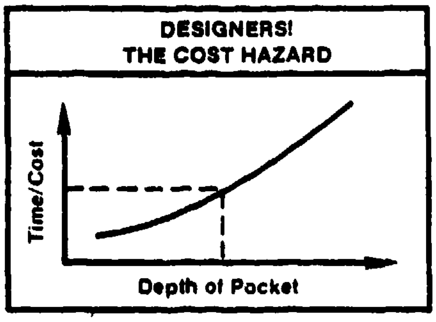




Specific Quantities Depend on:
- **Part Configuration**
- **Net (As Forged) Surfaces**

EFFECT OF METAL REMOVED ON MACHINING TIME

DEEP POCKET VS. SHALLOW (RIGID) POCKET



ALUMINUM

Depth	Time to Complete Pocket in Minutes
1/2"	0.2
1"	0.4
2"	0.8
3"	1.2

TITANIUM

Depth	Time to Complete Pocket in Minutes
1/2"	2.2
1"	4.4
2"	8.8
3"	13.2

HIGH STRENGTH STEELS

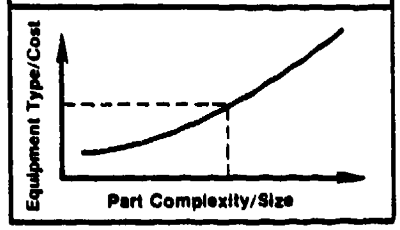
4340 Steel (Normalized)
Average of Aerospace Steels

Depth	Time to Complete Pocket in Minutes
1/2"	3.4
1"	6.8
2"	13.6
3"	20.4

INFLUENCE OF:
- **PART SIZE**
- **PART COMPLEXITY**
- **LOT SIZE**

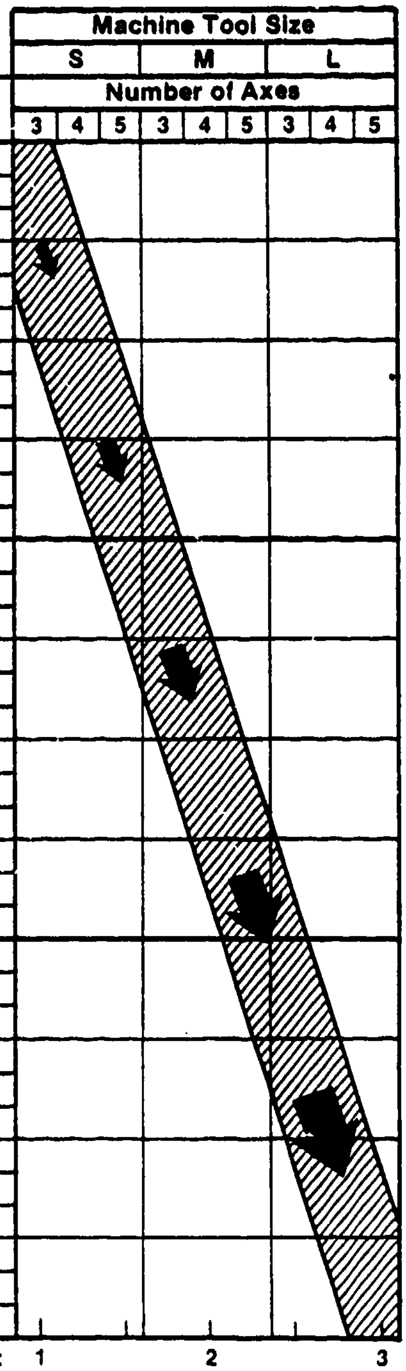
ON MACHINE TOOL SELECTION AND OPERATING COST

DESIGNERS! THE COST HAZARD



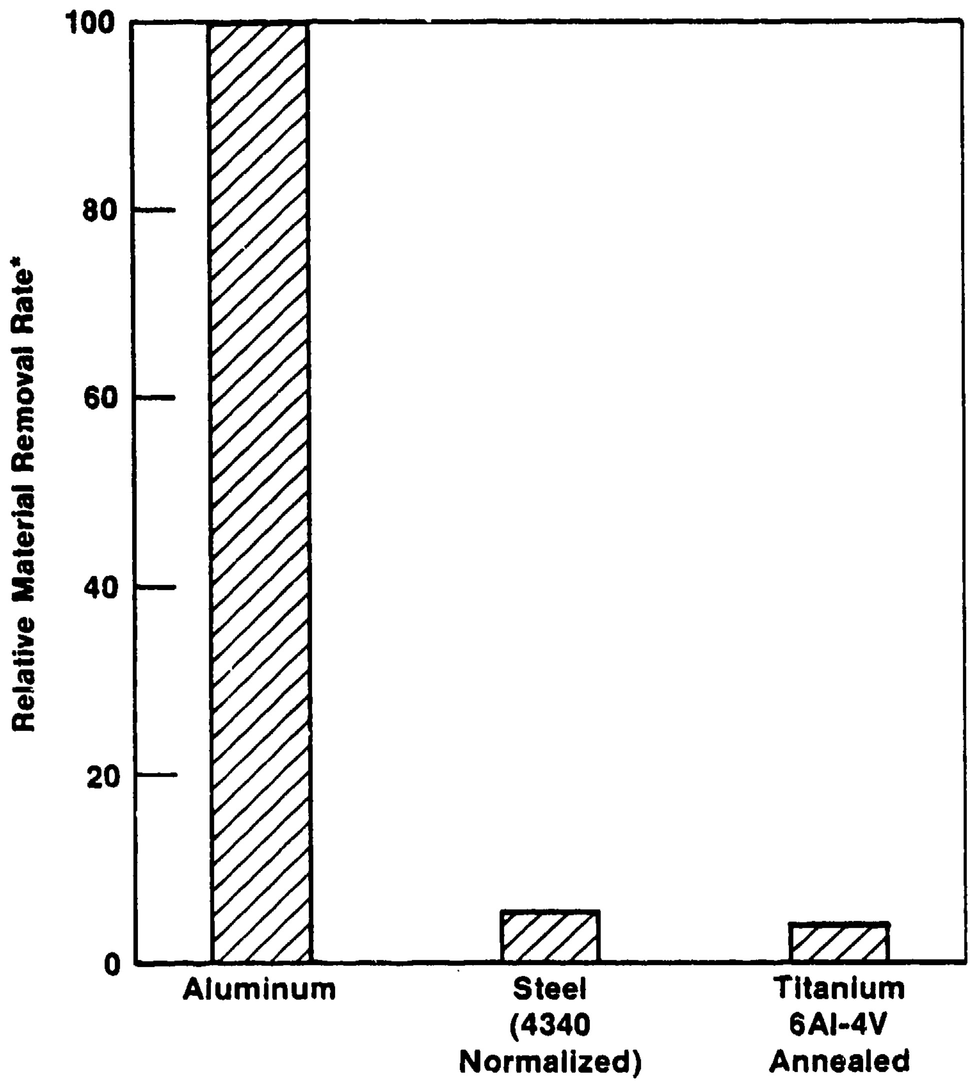
S	M	L
Small	Medium	Large

Part Size	Complexity	Lot Size
Small	Simple	S: 1-10
		M: 10-30
		L: 30 →
	Average	S: 1-10
		M: 10-30
		L: 30 →
	Complex	S: 1-10
		M: 10-30
		L: 30 →
	Exotic	S: 1-10
		M: 10-30
		L: 30 →
Medium	Simple	S: 1-10
		M: 10-30
		L: 30 →
	Average	S: 1-10
		M: 10-30
		L: 30 →
	Complex	S: 1-10
		M: 10-30
		L: 30 →
	Exotic	S: 1-10
		M: 10-30
		L: 30 →
Large	Simple	S: 1-10
		M: 10-30
		L: 30 →
	Average	S: 1-10
		M: 10-30
		L: 30 →
	Complex	S: 1-10
		M: 10-30
		L: 30 →
	Exotic	S: 1-10
		M: 10-30
		L: 30 →



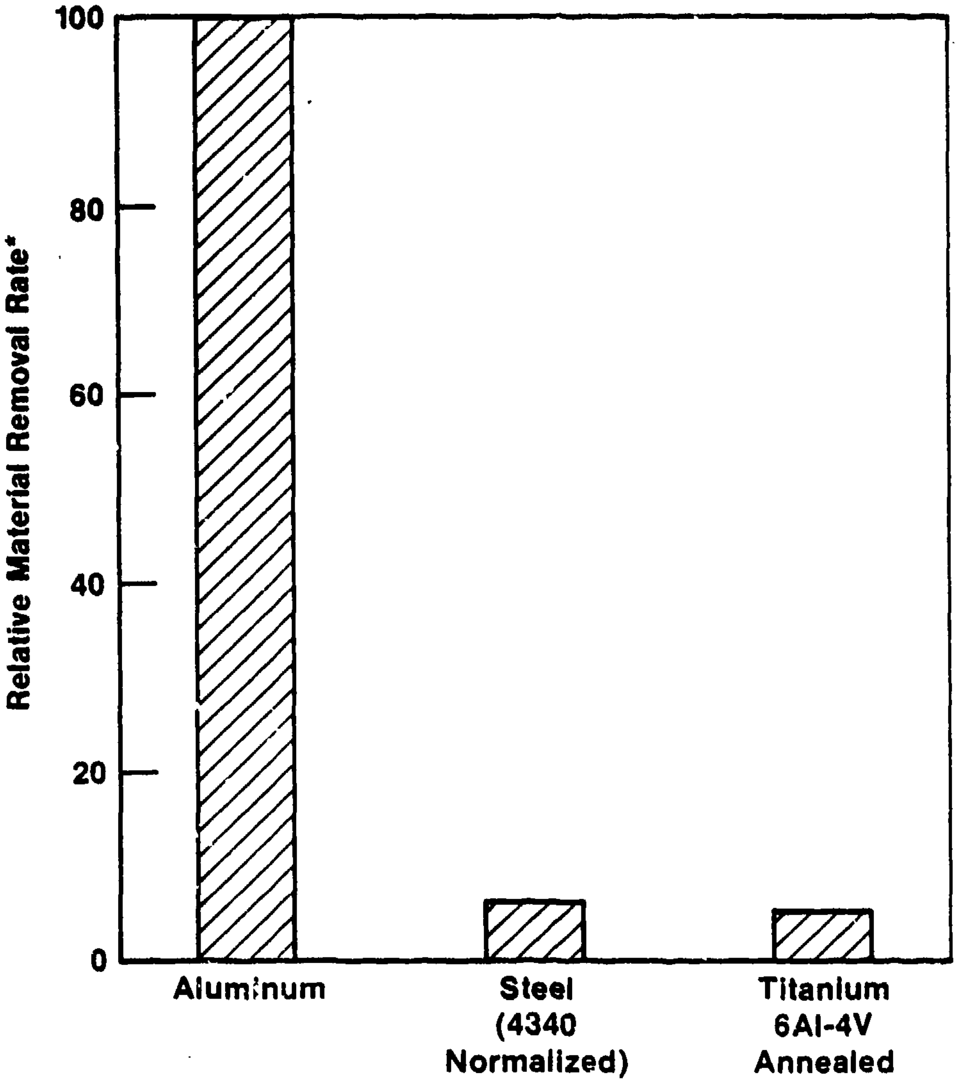
Relative Operating Cost: 1 2 3

RELATIVE TIME TO MACHINE FOR TURNING



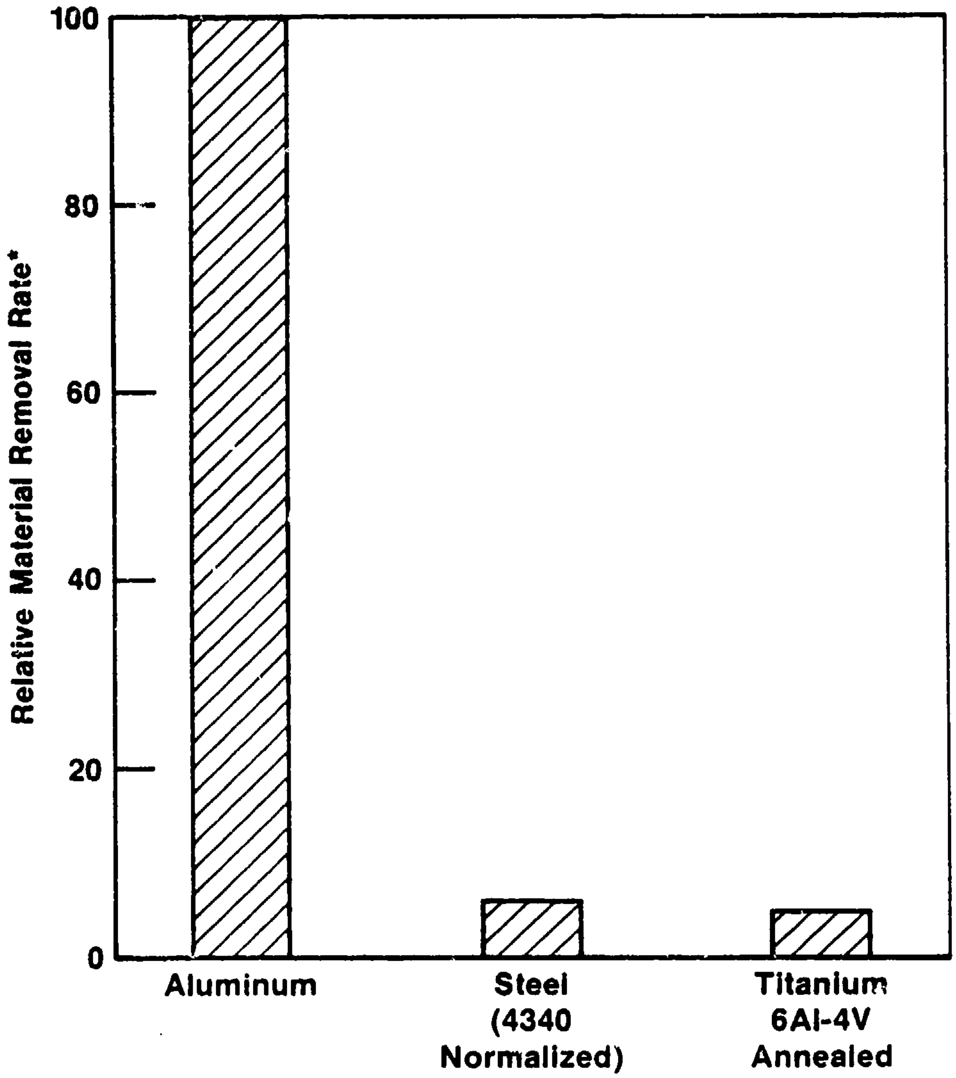
*Volumetric Cutting Rate; Exclusive of Setup and Handling

RELATIVE TIME TO MACHINE FOR END-MILLING



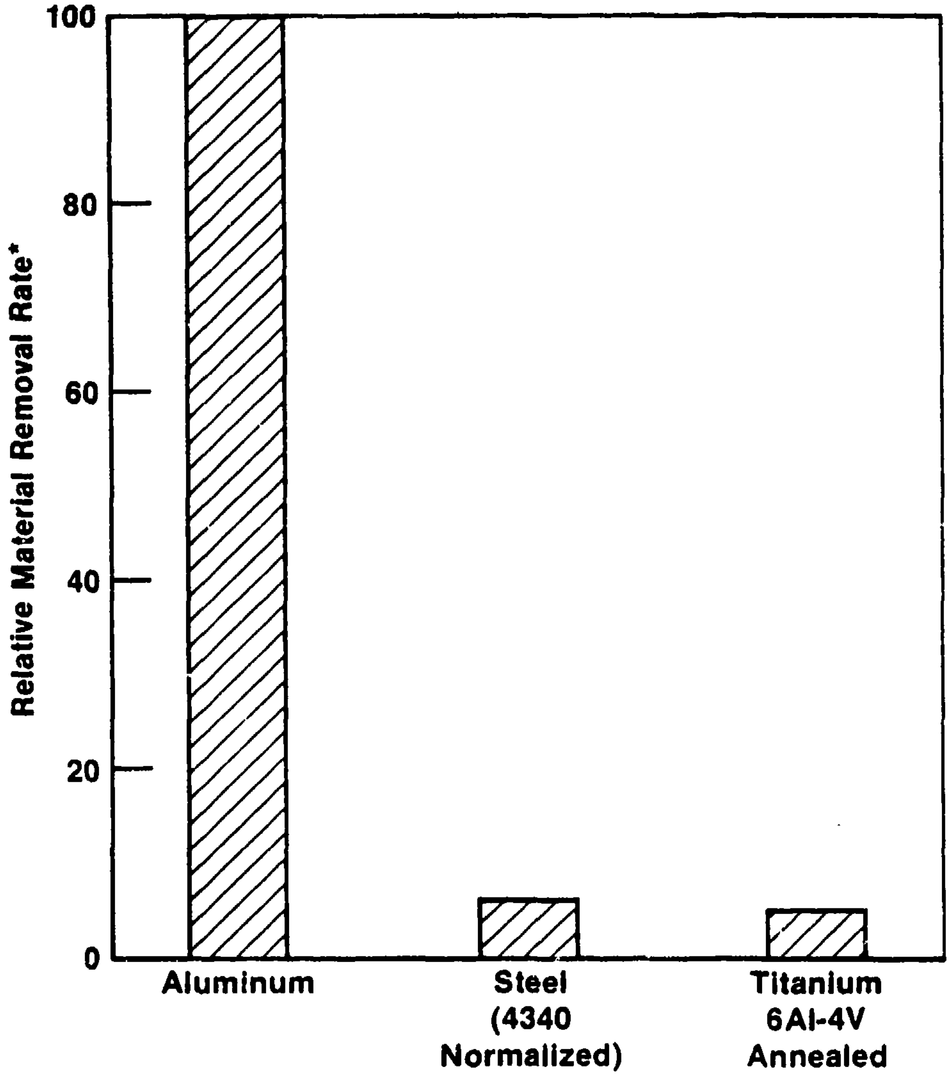
*Volumetric Cutting Rate; Exclusive of Setup and Handling

RELATIVE TIME TO MACHINE FOR DRILLING



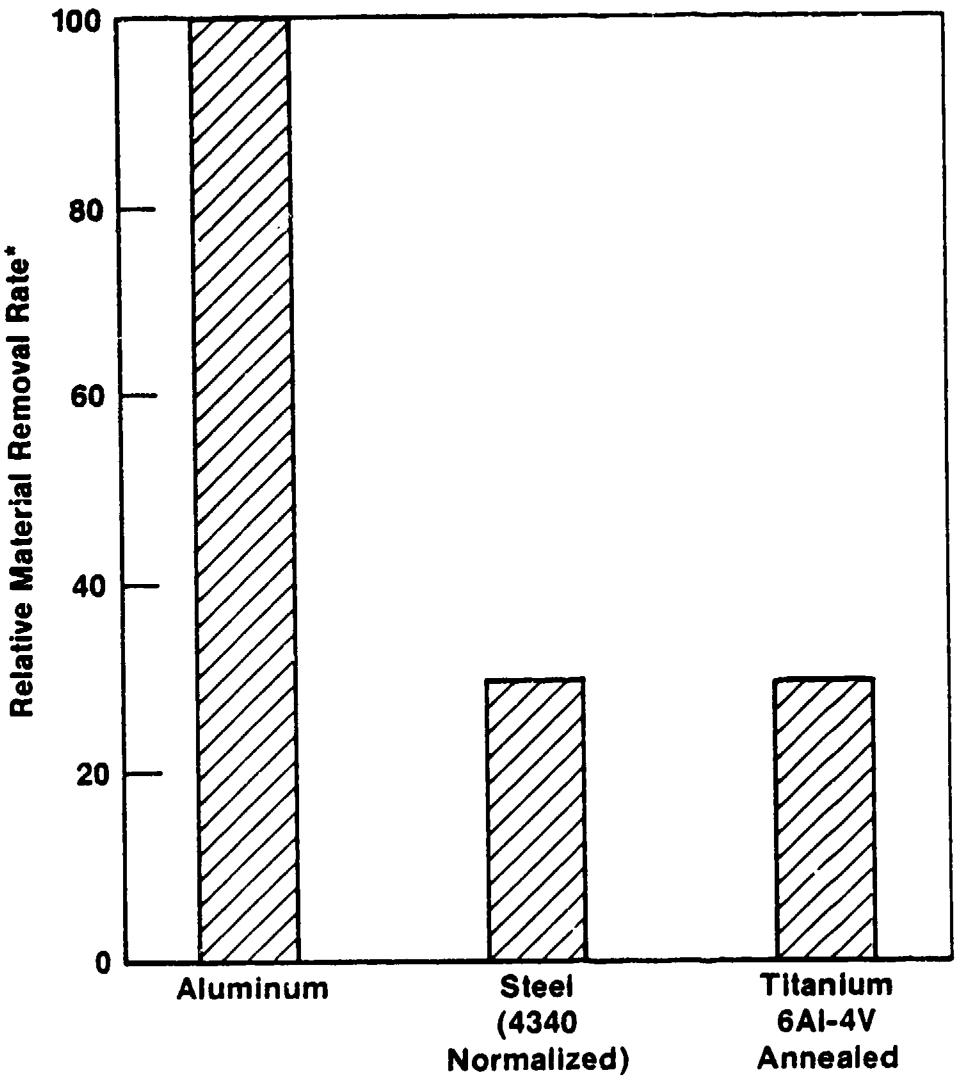
*Volumetric Cutting Rate; Exclusive of Setup and Handling

RELATIVE TIME TO MACHINE FOR REAMING



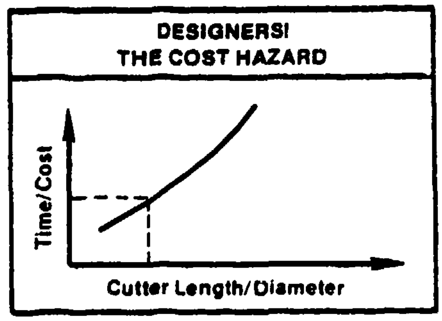
*Volumetric Cutting Rate; Exclusive of Setup and Handling

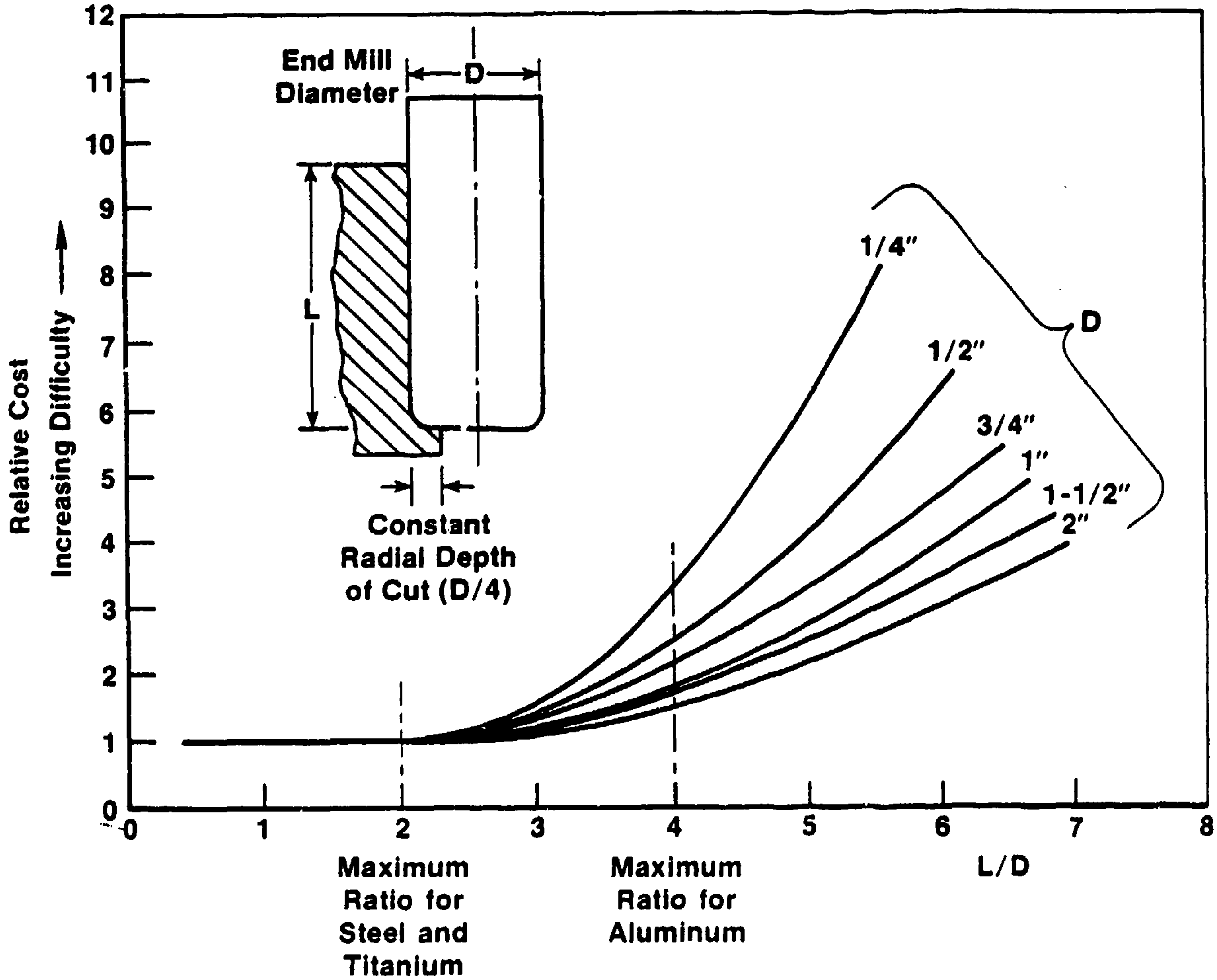
RELATIVE TIME TO MACHINE FOR TAPPING



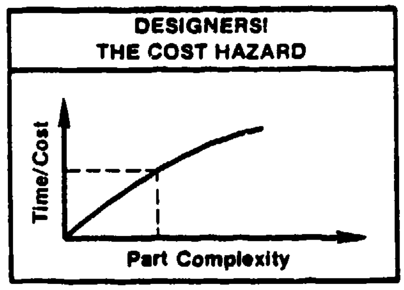
*Volumetric Cutting Rate; Exclusive of Setup and Handling

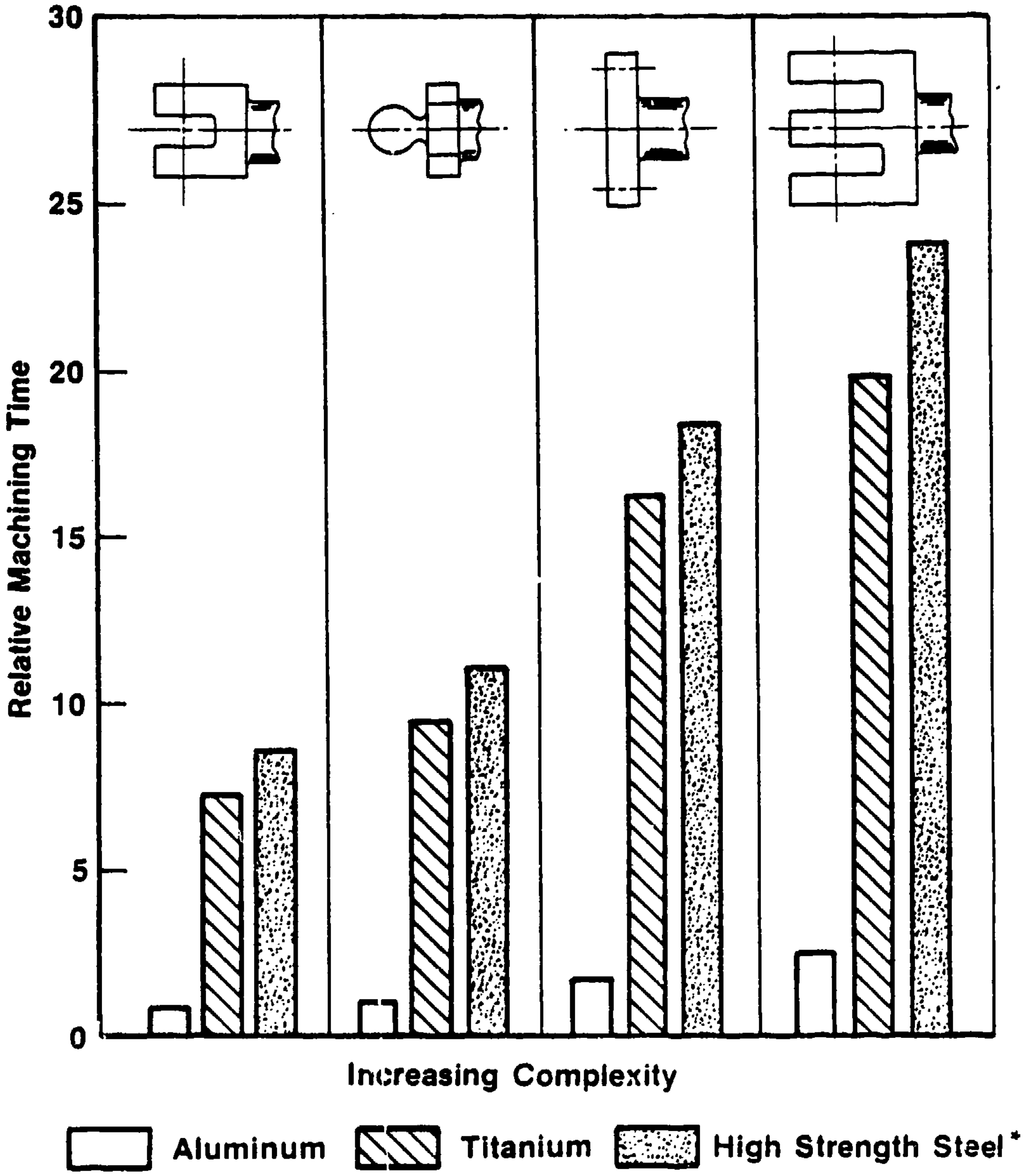
EFFECT OF CUTTER DIAMETER ON MACHINABILITY FACTOR





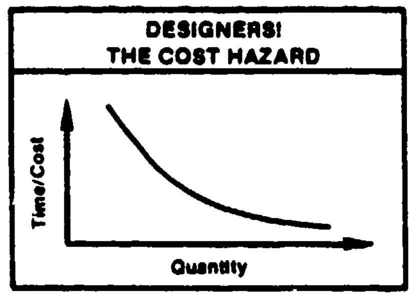
RELATIVE COST OF INCREASING PART COMPLEXITY

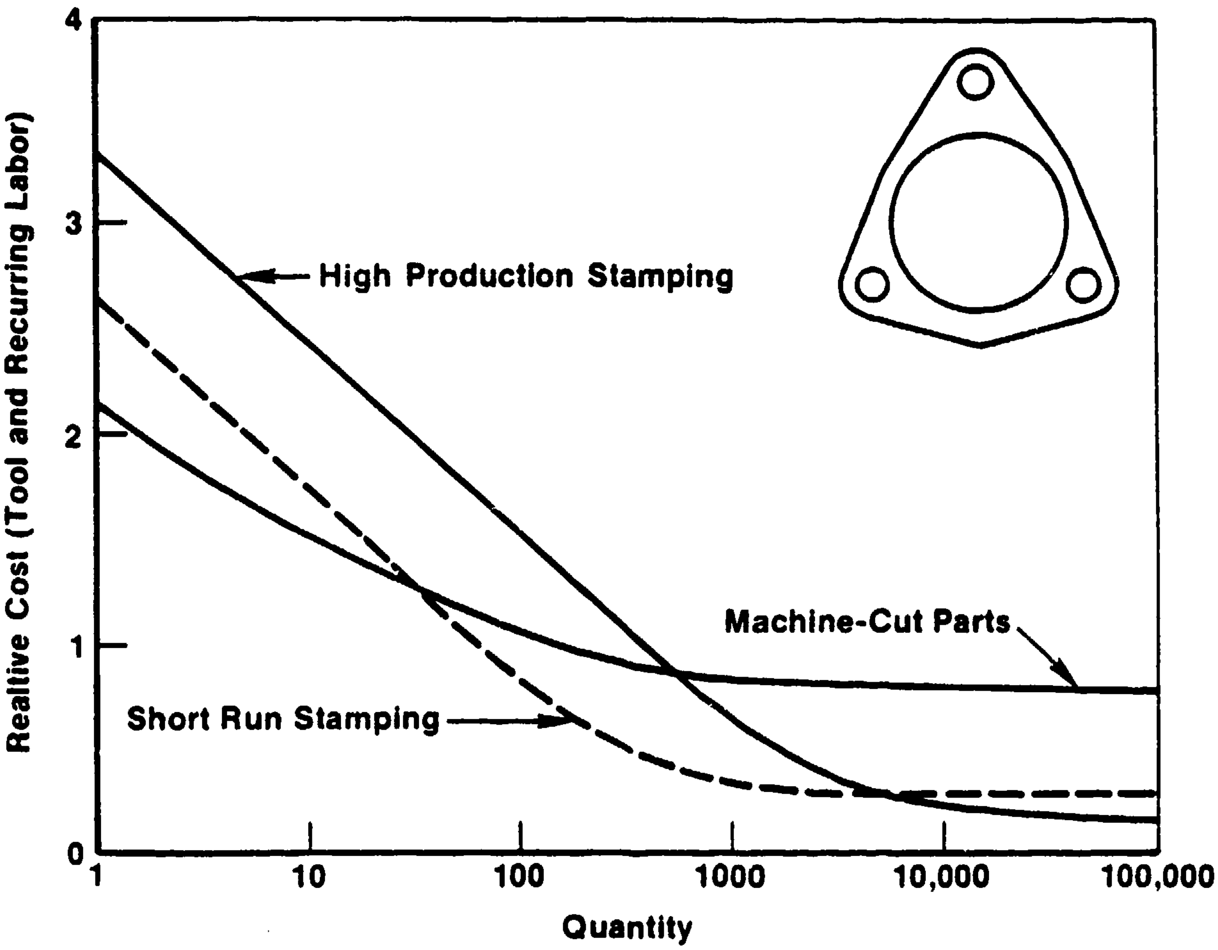




*After Heat-Treatment (Prior to Heat-Treatment Will be Less Than Titanium)

RELATIVE COST OF STAMPING VS. MACHINING FOR A SPECIFIC TYPE OF SHEET METAL PART





FORMAT SELECTION AID

MACHINING OF METALS

MACHINING FEATURES OF:
FRAMES, BULKHEADS, WING SKINS, BEAMS, SPARS, RIBS, STIFFENERS AND LONGERONS

MATERIAL FORMS:
FORGINGS AND PLATES

TAPER (PLATE)
CED-M/C-1

SKIN/STIFFENERS
CED-M/C-2

RIB/STIFFENERS
CED-M/C-3/5

FLANGE/RIB HEIGHT
CED-M/C-6/11

POCKETS
CED-M/C-12/15

SLOTS
CED-M/C-16

CURVED FLANGES
CED-M/C-17/21

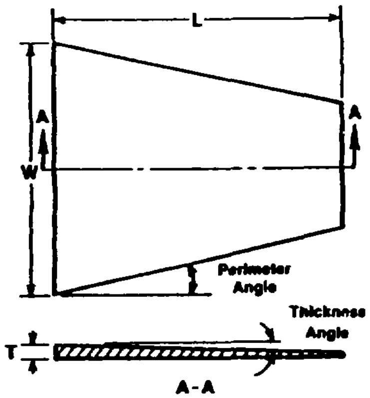
CORNER RADIUS
(END-MILL DIAMETER)
CED-M/C-22

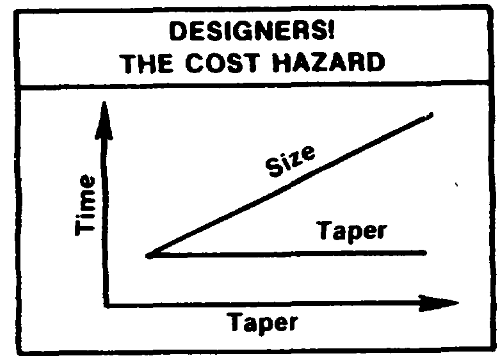
ROUGH/FINISH MACHINING
CED-M/C-23/26

SECONDARY MACHINING
CED-M/C-27/28

EFFECT OF PERIMETER AND THICKNESS TAPER ON MACHINING TIME FOR:

ALUMINUM

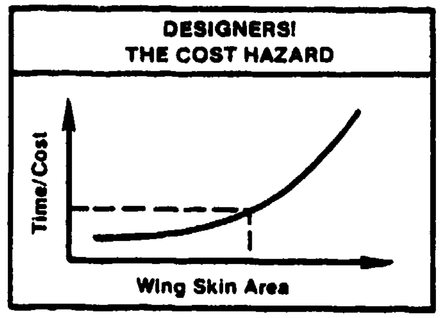


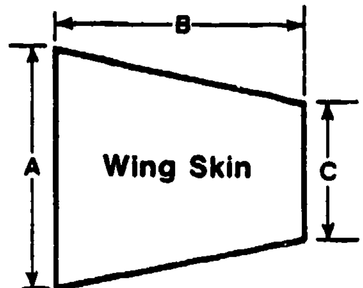


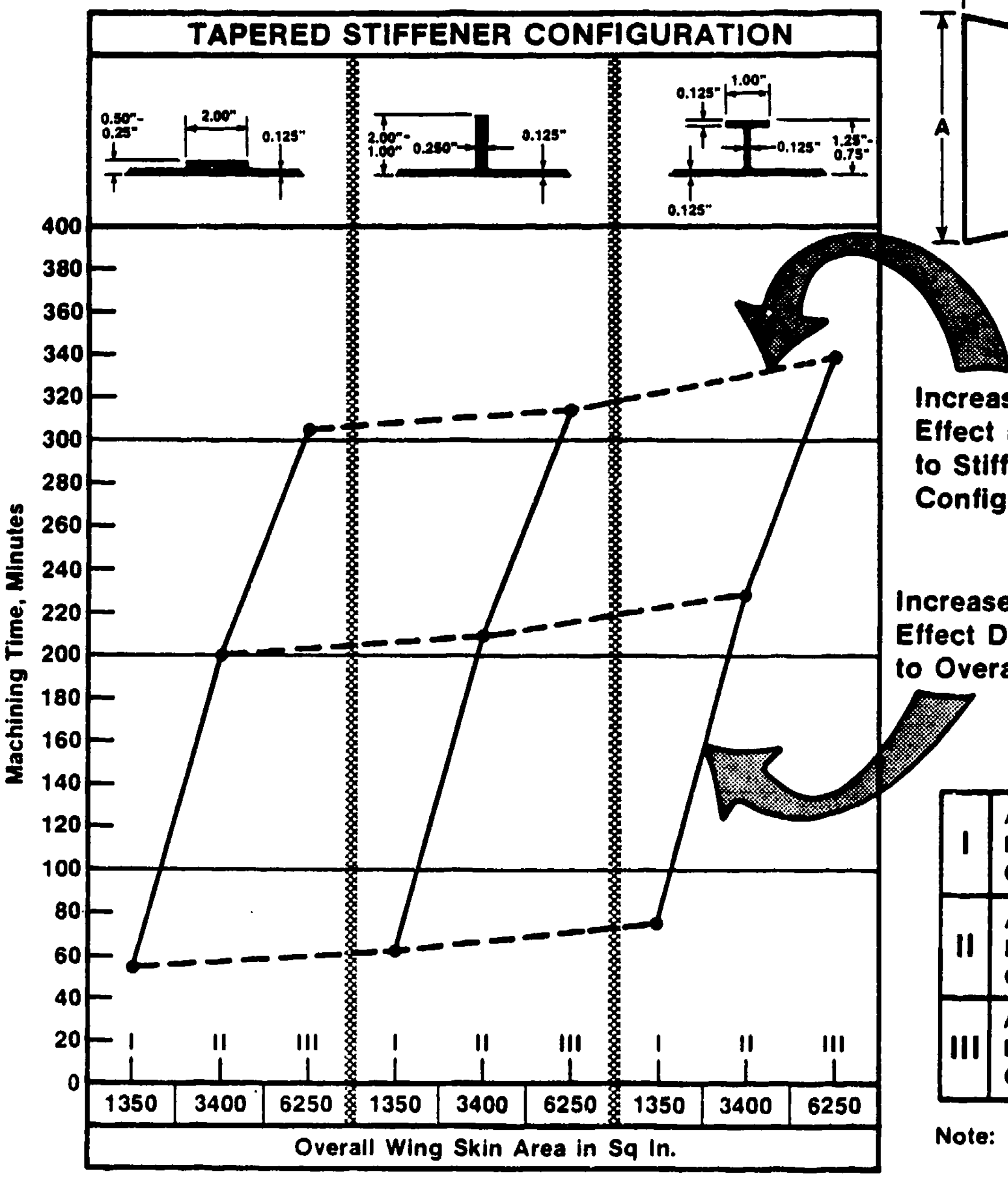
Part No.	Part Dimensions			Taper		Relative Cost
	Length	Width	Thickness	Thickness	Perimeter	
I	48.75"	30.5"	0.50"	0°-1°	0°-20°	28
				1°-2°	20°-40°	28
				2°-3°	40°-60°	28
II	38"	24"	0.625"	0°-1°	0°-20°	26
				1°-2°	20°-40°	26
				2°-3°	40°-60°	26
III	24"	18"	0.625"	-	0°-20°	24
				-	20°-40°	24
				-	40°-60°	24

EFFECT OF STIFFENER CONFIGURATION AND WING SKIN PLAN AREA ON MACHINING TIME

ALUMINUM







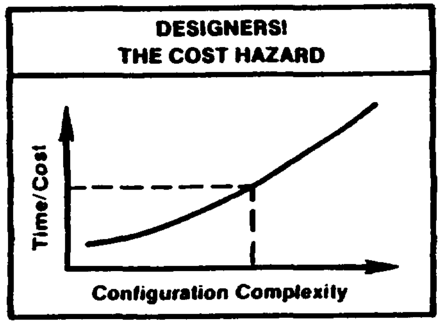
Increased Time Effect Due to Stiffener Configuration

Increased Time Effect Due to Overall Size

I	A = 25" B = 60" C = 20"	1350 Sq. In.
II	A = 50" B = 80" C = 35"	3400 Sq. In.
III	A = 80" B = 100" C = 45"	6250 Sq. In.

Note: Each Panel to Have Five Equal Stiffeners

EFFECT OF RIB/STRINGER CONFIGURATION ON MACHINING TIME



ALUMINUM

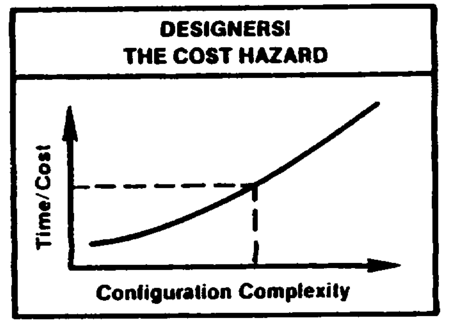
(Sketches of Parts Follow)

Configuration	Thickness of Rib (1 or 2)	Height of Rib (A or B)	Width of Lip (X or Y)	Angle (10°-30°-45°)	Time in Minutes to Machine 10" Length
I	-	1.000"	-	-	1.2
I	-	3.000"	-	-	3.4
II	0.060"	0.750"	-	-	4.0
II	0.060"	2.000"	-	-	8.0
II	0.125"	0.750"	-	-	2.2
II	0.125"	2.000"	-	-	4.0
III	0.060"	1.000"	-	10°	3.4
III	0.060"	1.000"	-	30°	3.4
III	0.060"	1.000"	-	45°	3.4
III	0.060"	2.000"	-	10°	7.4
III	0.060"	2.000"	-	30°	7.4
III	0.060"	2.000"	-	45°	7.4
III	0.125"	1.000"	-	10°	1.6
III	0.125"	1.000"	-	30°	1.6
III	0.125"	1.000"	-	45°	1.6
III	0.125"	2.000"	-	10°	3.4
III	0.125"	2.000"	-	30°	3.4
III	0.125"	2.000"	-	45°	3.4
IV	0.125"	1.500"	1.000"	-	5.4
IV	0.125"	1.500"	1.000"	-	5.5
IV	0.125"	0.750"	0.500"	-	3.9
IV	0.125"	0.750"	0.500"	-	3.9
V	0.250"	1.500"	1.000"	-	5.6
V	0.250"	0.750"	1.000"	-	4.0

EFFECT OF RIB/STRINGER CONFIGURATION ON MACHINING TIME

TITANIUM

(Sketches of Parts Follow)



Configuration	1 or 2 Thickness of Rib	A or B Height of Rib	X or Y Width of Lip	10°-30°-45° Angle	Time in Minutes to Machine 10" Length
I	-	1.000"	-	-	3.0
I	-	3.000"	-	-	8.5
II	0.060"	0.750"	-	-	10.0
II	0.060"	2.000"	-	-	20.0
II	0.125"	0.750"	-	-	4.0
II	0.125"	2.000"	-	-	10.0
III	0.060"	1.000"	-	10°	8.5
III	0.060"	1.000"	-	30°	8.5
III	0.060"	1.000"	-	45°	8.5
III	0.060"	2.000"	-	10°	18.5
III	0.060"	2.000"	-	30°	18.5
III	0.060"	2.000"	-	45°	18.5
III	0.125"	1.000"	-	10°	4.0
III	0.125"	1.000"	-	30°	4.0
III	0.125"	1.000"	-	45°	4.0
III	0.125"	2.000"	-	10°	8.5
III	0.125"	2.000"	-	30°	8.5
III	0.125"	2.000"	-	45°	8.5
IV	0.125"	1.500"	1.000"	-	13.5
IV	0.125"	1.500"	1.000"	-	13.8
IV	0.125"	0.750"	0.500"	-	9.8
IV	0.125"	0.750"	0.500"	-	9.8
V	0.250"	1.500"	1.000"	-	14.0
V	0.250"	0.750"	1.000"	-	10.0

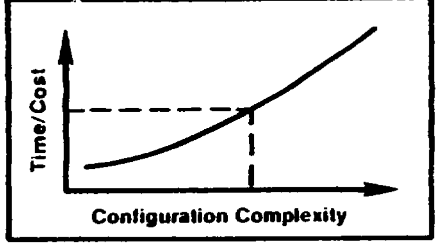
CED-M/C-4

EFFECT OF RIB/STRINGER CONFIGURATION ON MACHINING TIME

HIGH STRENGTH STEELS

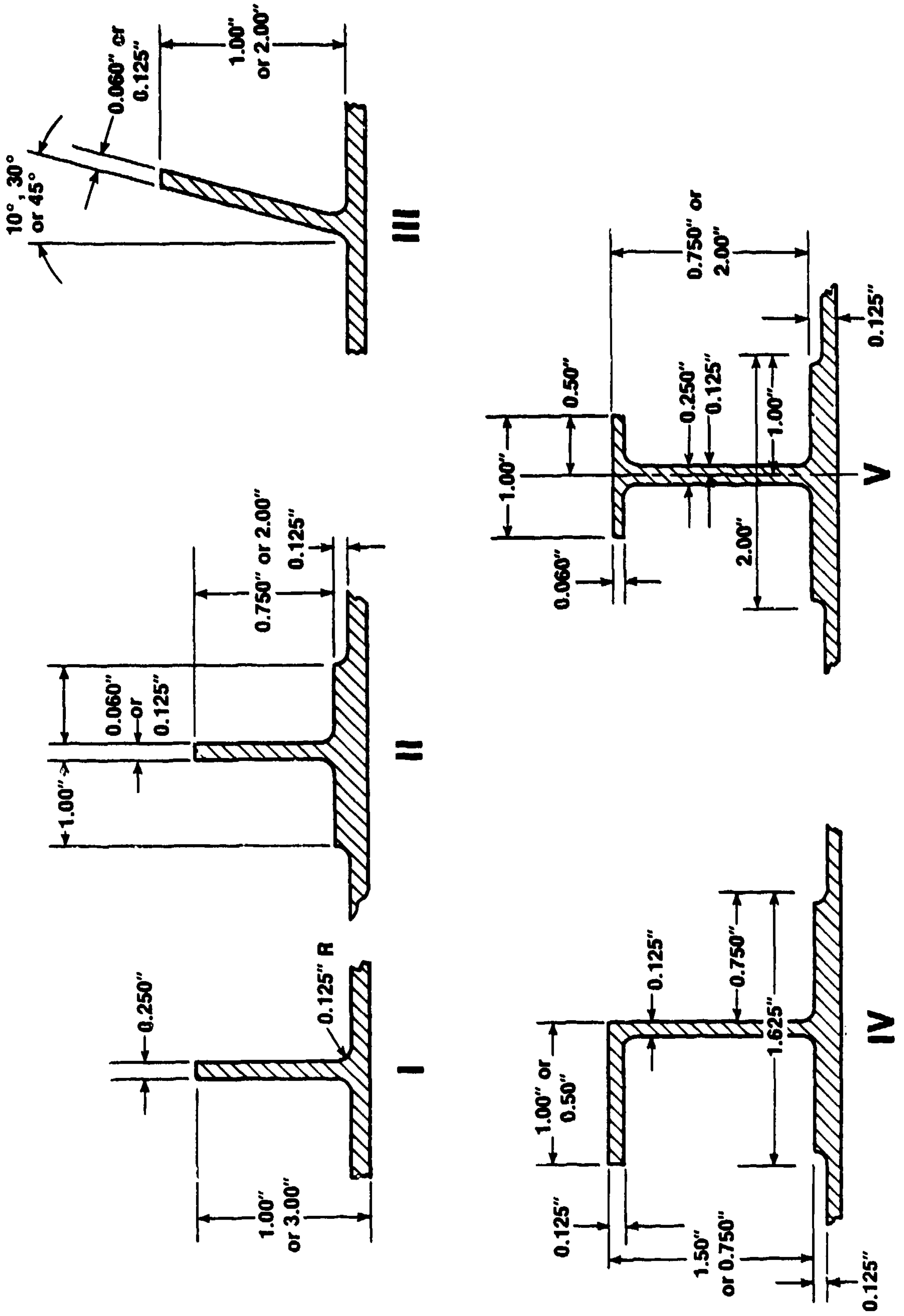
(Sketches of Parts Follow)

DESIGNERS!
THE COST HAZARD



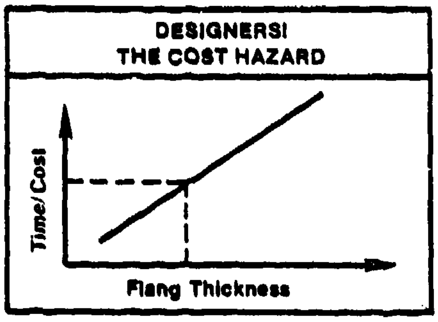
4340 Steel (Normalized)
Average of Aerospace Steels

Configuration	1 or 2 Thickness of Rib	A or B Height of Rib	X or Y Width of Lip	10°-30°-45° Angle	Time in Minutes to Machine 10" Length
I	-	A = 1.000"	-	-	6.0
I	-	3.000"	-	-	17.0
II	0.060"	0.750"	-	-	20.0
II	0.060"	2.000"	-	-	40.0
II	0.125"	0.750"	-	-	11.0
II	0.125"	2.000"	-	-	20.0
III	0.060"	1.000"	-	10°	17.0
III	0.060"	1.000"	-	30°	17.0
III	0.060"	1.000"	-	45°	17.0
III	0.060"	2.000"	-	10°	37.0
III	0.060"	2.000"	-	30°	37.0
III	0.060"	2.000"	-	45°	37.0
III	0.125"	1.000"	-	10°	8.0
III	0.125"	1.000"	-	30°	8.0
III	0.125"	1.000"	-	45°	4.0
III	0.125"	2.000"	-	10°	17.0
III	0.125"	2.000"	-	30°	17.0
III	0.125"	2.000"	-	45°	17.0
IV	0.125"	1.500"	1.000"	-	27.0
IV	0.125"	1.500"	1.000"	-	27.6
IV	0.125"	0.750"	0.500"	-	19.6
IV	0.125"	0.750"	0.500"	-	19.6
V	0.250"	1.500"	-	-	28.0
V	0.250"	0.750"	-	-	20.0



STRINGER CONFIGURATIONS STUDIED TO DEVELOP FORMATS: CED-M/C-3 to CED-M/C-5

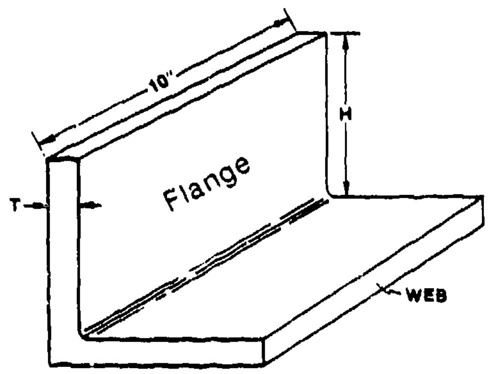
EFFECT OF HEIGHT AND THICKNESS ON MACHINING TIME



ALUMINUM

UNSUPPORTED LENGTHWISE

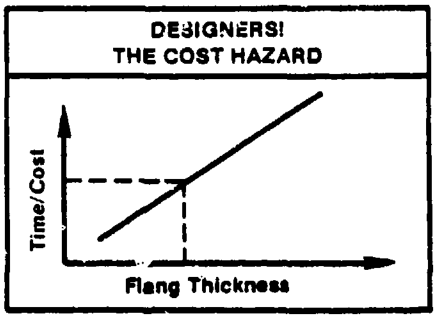
Rib H	Rib T	Time in Minutes to Machine 10" Length
1"	1/16"	1.7
	1/8"	0.8
	1/4"	0.6
	1/2"	0.4
	1"	0.3
2"	1/16"	3.7
	1/8"	1.7
	1/4"	0.8
	1/2"	0.4
	1"	0.3
3"	1/16"	8.7
	1/8"	3.7
	1/4"	1.7
	1/2"	0.8
	1"	0.3



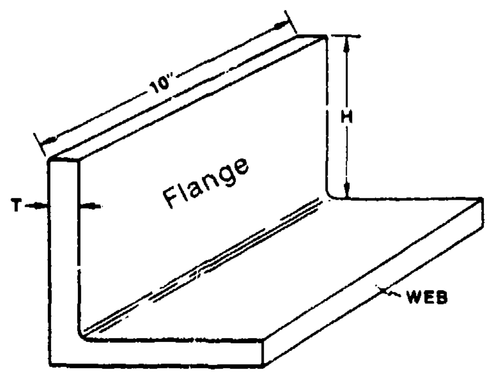
EFFECT OF HEIGHT AND THICKNESS ON MACHINING TIME

TITANIUM

UNSUPPORTED LENGTHWISE



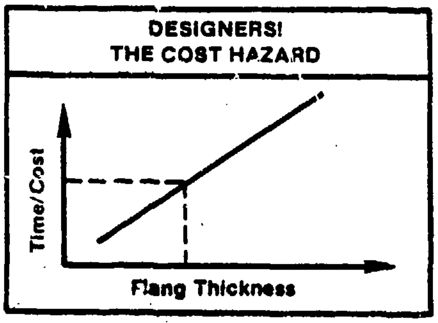
Rib H	Rib T	Time in Minutes to Machine 10" Length
1"	1/16"	3.12
	1/8"	2.10
	1/4"	1.25
	1/2"	1.00
	1"	1.00
2"	1/16"	6.25
	1/8"	3.12
	1/4"	1.60
	1/2"	1.25
	1"	1.00
3"	1/16"	12.50
	1/8"	6.25
	1/4"	2.10
	1/2"	1.25
	1"	1.00



EFFECT OF HEIGHT AND THICKNESS ON MACHINING TIME

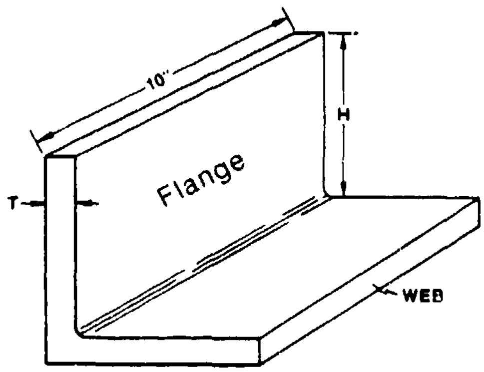
HIGH STRENGTH STEELS

UNSUPPORTED LENGTHWISE



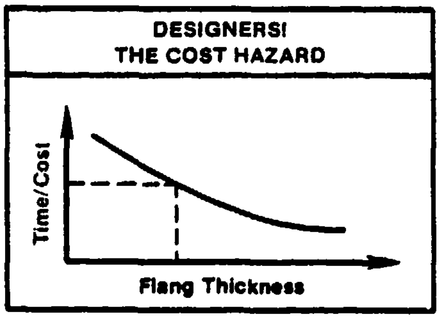
Rib H	Rib T	Time in Minutes to Machine 10" Length
1"	1/16"	20.0
	1/8"	12.0
	1/4"	9.0
	1/2"	6.0
	1"	6.0
2"	1/16"	30.0
	1/8"	20.0
	1/4"	12.0
	1/2"	9.0
	1"	6.0
3"	1/16"	60.0
	1/8"	30.0
	1/4"	20.0
	1/2"	12.0
	1"	9.0

4340 Steel (Normalized) — Average of Aerospace Steels



CED-M/C-8

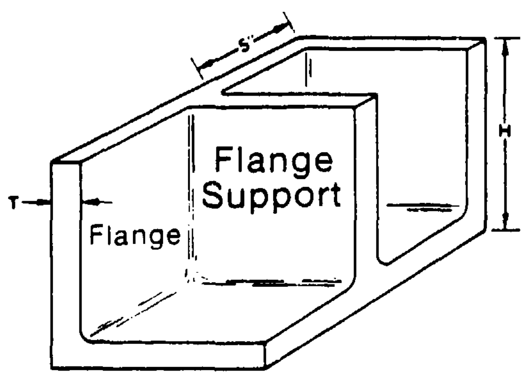
EFFECT OF HEIGHT AND THICKNESS ON MACHINING TIME



ALUMINUM

SUPPORTED LENGTHWISE AT 5-INCH INTERVALS

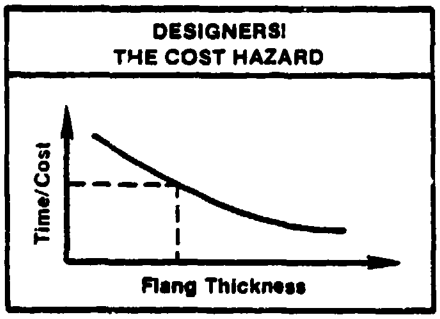
Rib H	Rib T	Time in Minutes to Machine 10" Length
1"	1/16"	1.2
	1/8"	0.6
	1/4"	0.5
	1/2"	0.3
	1"	0.3
2"	1/16"	2.8
	1/8"	1.2
	1/4"	0.5
	1/2"	0.3
	1"	0.3
3"	1/16"	4.9
	1/8"	2.8
	1/4"	1.2
	1/2"	0.6
	1"	0.3



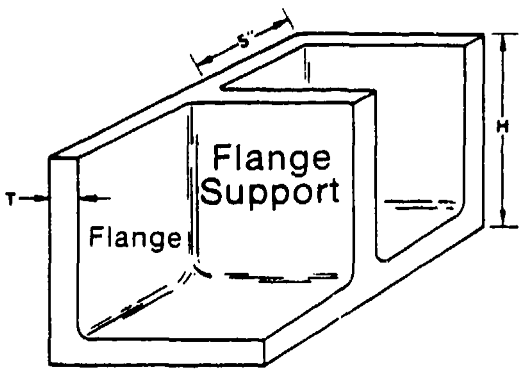
EFFECT OF HEIGHT AND THICKNESS ON MACHINING TIME

TITANIUM

SUPPORTED LENGTHWISE AT 5-INCH INTERVALS



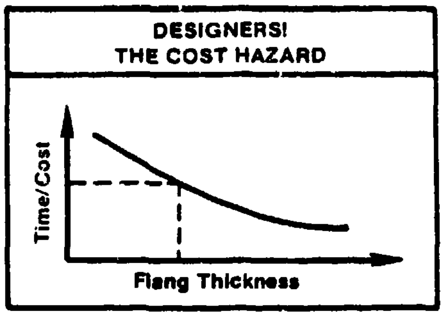
Rib H	Rib T	Time in Minutes to Machine 10" Length
1"	1/16"	2.25
	1/8"	1.60
	1/4"	1.15
	1/2"	1.00
	1"	1.00
2"	1/16"	4.75
	1/8"	2.25
	1/4"	1.40
	1/2"	1.20
	1"	1.00
3"	1/16"	8.00
	1/8"	5.75
	1/4"	2.00
	1/2"	1.15
	1"	1.00



EFFECT OF HEIGHT AND THICKNESS ON MACHINING TIME

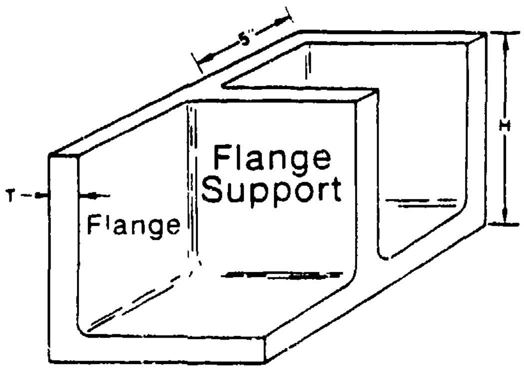
HIGH STRENGTH STEELS

SUPPORTED LENGTHWISE AT 5-INCH INTERVALS



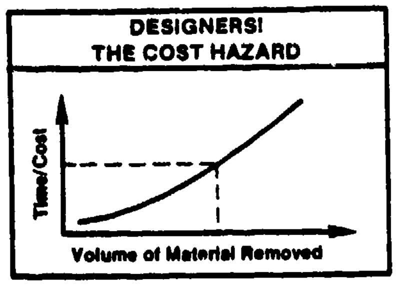
Rib H	Rib T	Time in Minutes to Machine 10" Length
1"	1/16"	16.0
	1/8"	9.6
	1/4"	7.5
	1/2"	6.0
	1"	6.0
2"	1/16"	25.0
	1/8"	16.0
	1/4"	10.0
	1/2"	8.5
	1"	6.0
3"	1/16"	40.0
	1/8"	24.0
	1/4"	16.0
	1/2"	10.0
	1"	8.0

4340 Steel (Normalized) Average of Aerospace Steels



CED-M/C-11

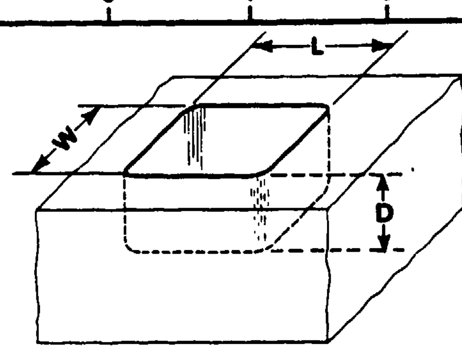
EFFECT OF POCKET/SLOT SIZE AND CONFIGURATION ON MACHINING TIME



ALUMINUM

Time to Machine Pocket, Minutes

Volume of Pocket/Slot Cu. In.	Dimensions of Pocket/Slot W	L	D
1	1"	1"	1"
	1/2"	2"	1"
	1/4"	4"	1"
	1"	2"	1/2"
	1/2"	4"	1/2"
	1/4"	8"	1/2"
2 Doubling Width	2"	1"	1"
	1"	2"	1"
	1/2"	4"	1"
	2"	2"	1/2"
	1"	4"	1/2"
	1/2"	8"	1/2"
2 Doubling Length	1"	2"	1"
	1/2"	4"	1"
	1/4"	8"	1"
	1"	4"	1/2"
	1/2"	8"	1/2"
	1/4"	16"	1/2"
2 Doubling Depth	1"	1"	2"
	1/2"	2"	2"
	1/4"	4"	2"
	1"	2"	1"
	1/2"	4"	1"
	1/4"	8"	1"
4 Doubling Depth & Length	1"	2"	2"
	1/2"	4"	2"
	1/4"	8"	2"
	1"	4"	1"
	1/2"	8"	1"
	1/4"	16"	1"
4 Doubling Depth & Width	2"	1"	2"
	1"	2"	2"
	1/2"	4"	2"
	2"	2"	1"
	1"	4"	1"
	1/2"	8"	1"
4 Doubling Width & Length	2"	2"	1"
	1"	4"	1"
	1/2"	8"	1"
	2"	4"	1/2"
	1"	8"	1/2"
	1/2"	16"	1/2"
8 Doubling Width, Length & Depth	2"	2"	2"
	1"	4"	2"
	1/2"	8"	2"
	2"	4"	1"
	1"	8"	1"
	1/2"	16"	1"

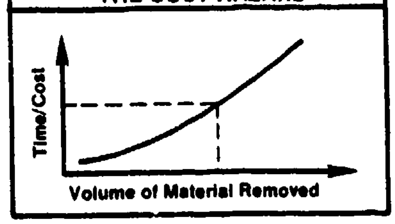


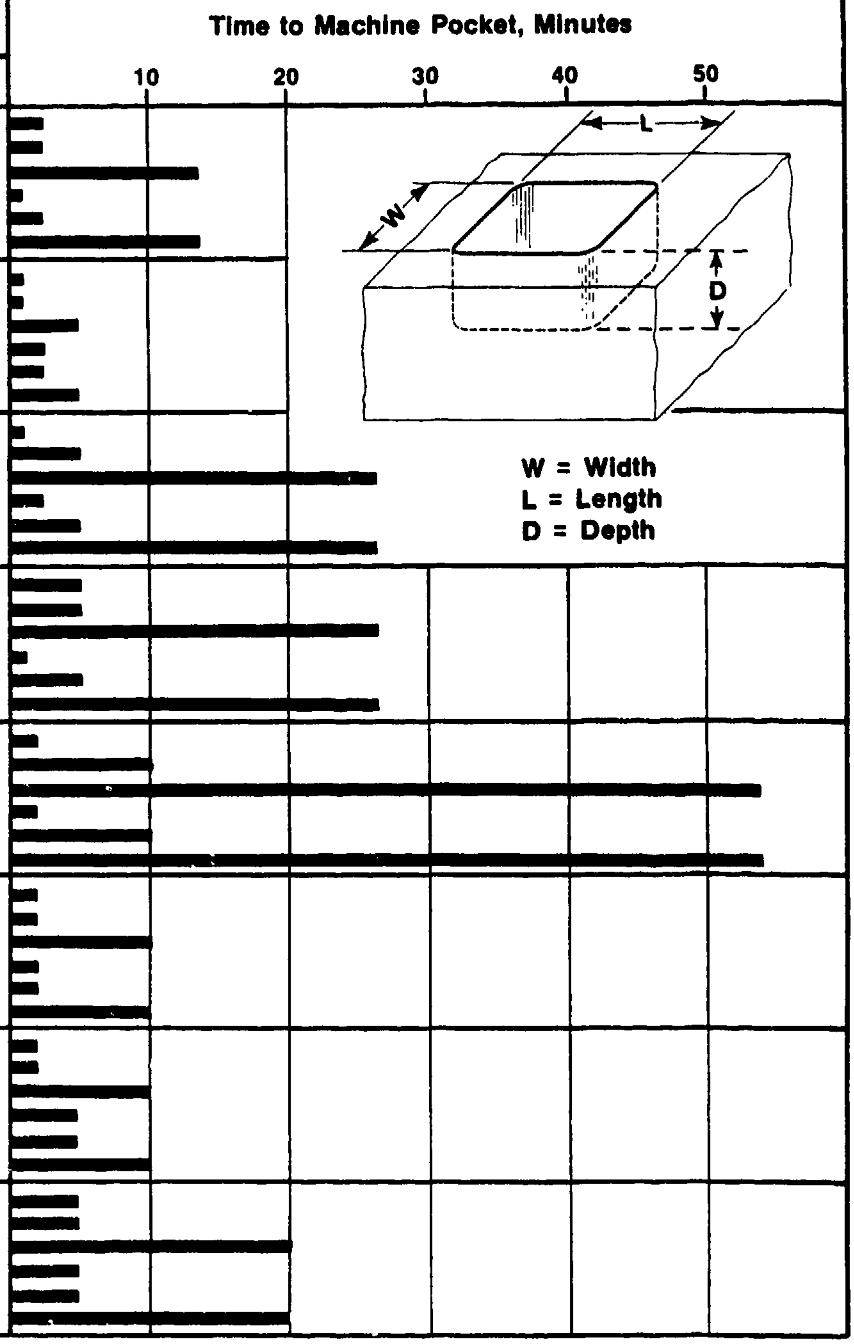
W = Width
L = Length
D = Depth

CED-M/C-12

EFFECT OF POCKET/SLOT SIZE AND CONFIGURATION ON MACHINING TIME

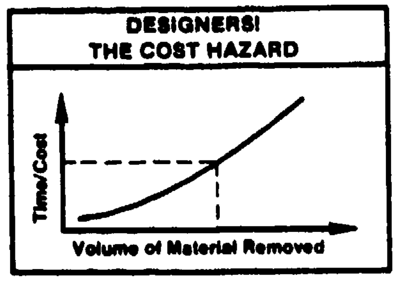
TITANIUM





Volume of Pocket/Slot Cu. In.	Dimensions of Pocket/Slot W	L	D
1	1"	1"	1"
	1/2"	2"	1"
	1/4"	4"	1"
	1"	2"	1/2"
	1/2"	4"	1/2"
	1/4"	8"	1/2"
2 Doubling Width	2"	1"	1"
	1"	2"	1"
	1/2"	4"	1"
	2"	2"	1/2"
	1"	4"	1/2"
	1/2"	8"	1/2"
2 Doubling Length	1"	2"	1"
	1/2"	4"	1"
	1/4"	8"	1"
	1"	4"	1/2"
	1/2"	8"	1/2"
	1/4"	16"	1/2"
2 Doubling Depth	1"	1"	2"
	1/2"	2"	2"
	1/4"	4"	2"
	1"	2"	1"
	1/2"	4"	1"
	1/4"	8"	1"
4 Doubling Depth & Length	1"	2"	2"
	1/2"	4"	2"
	1/4"	8"	2"
	1"	4"	1"
	1/2"	8"	1"
	1/4"	16"	1"
4 Doubling Depth & Width	2"	1"	2"
	1"	2"	2"
	1/2"	4"	2"
	2"	2"	1"
	1"	4"	1"
	1/2"	8"	1"
4 Doubling Width & Length	2"	2"	1"
	1"	4"	1'
	1/2"	8"	1"
	2"	4"	1/2"
	1"	8"	1/2"
	1/2"	16"	1/2"
8 Doubling Width, Length & Depth	2"	2"	2"
	1"	4"	2"
	1/2"	8"	2"
	2"	4"	1"
	1"	8"	1"
	1/2"	16'	1"

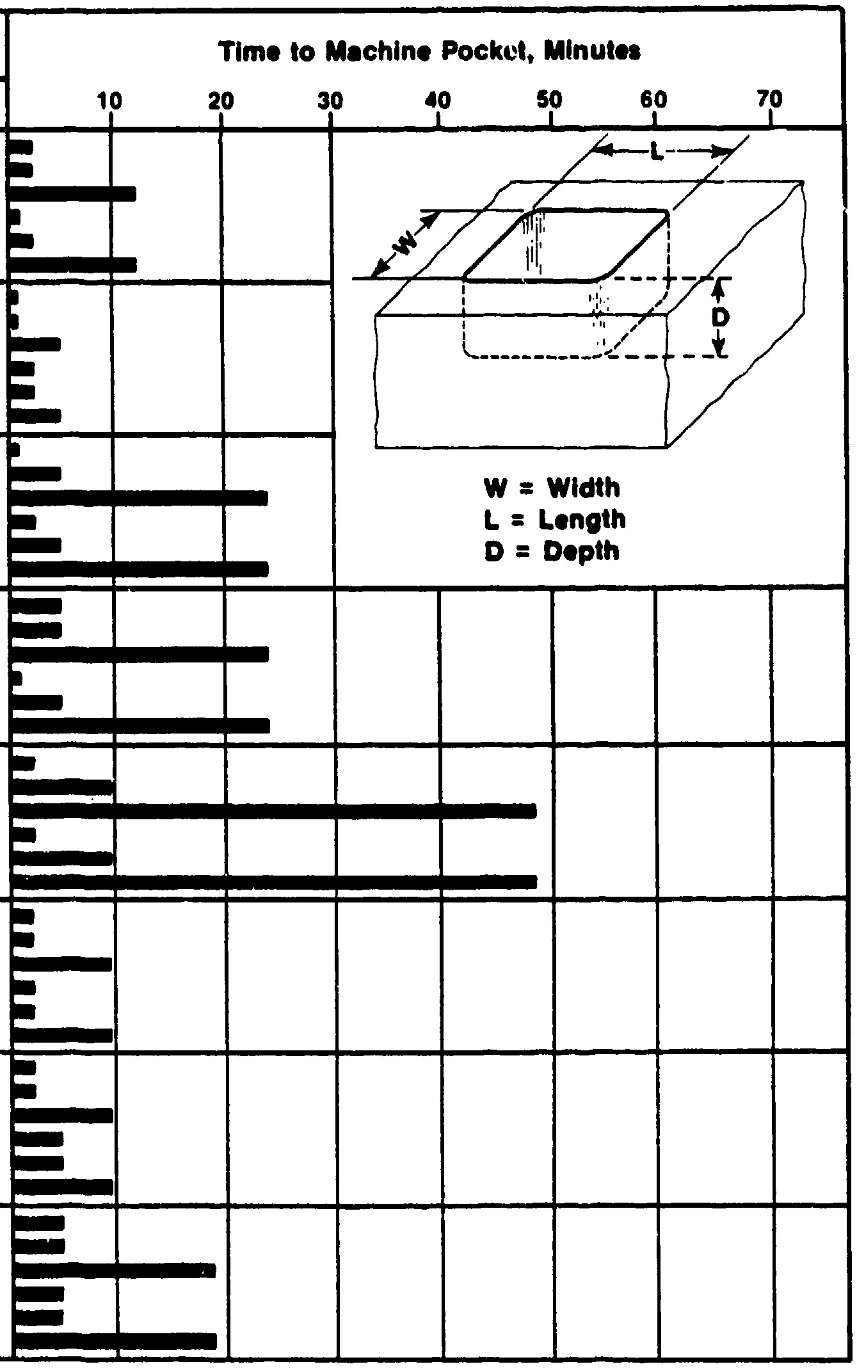
EFFECT OF POCKET/SLOT SIZE AND CONFIGURATION ON MACHINING TIME



HIGH STRENGTH STEELS

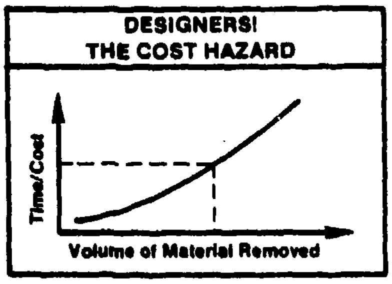
4340 Steel (Normalized)

Volume of Pocket/Slot Cu. In.	Dimensions of Pocket/Slot W	L	D
1	1"	1"	1"
	1/2"	2"	1"
	1/4"	4"	1"
	1"	2"	1/2"
	1/2"	4"	1/2"
	1/4"	8"	1/2"
2 Doubling Width	2"	1"	1"
	1"	2"	1"
	1/2"	4"	1"
	2"	2"	1/2"
	1"	4"	1/2"
	1/2"	8"	1/2"
2 Doubling Length	1"	2"	1"
	1/2"	4"	1"
	1/4"	8"	1"
	1"	4"	1/2"
	1/2"	8"	1/2"
	1/4"	16"	1/2"
2 Doubling Depth	1"	1"	2"
	1/2"	2"	2"
	1/4"	4"	2"
	1"	2"	1"
	1/2"	4"	1"
	1/4"	8"	1"
4 Doubling Depth & Length	1"	2"	2"
	1/2"	4"	2"
	1/4"	8"	2"
	1"	4"	1"
	1/2"	8"	1"
	1/4"	16"	1"
4 Doubling Depth & Width	2"	1"	2"
	1"	2"	2"
	1/2"	4"	2"
	2"	2"	1"
	1"	4"	1"
	1/2"	8"	1"
4 Doubling Width & Length	2"	2"	1"
	1"	4"	1"
	1/2"	8"	1"
	2"	4"	1/2"
	1"	8"	1/2"
	1/2"	16"	1/2"
8 Doubling Width, Length & Depth	2"	2"	2"
	1"	4"	2"
	1/2"	8"	2"
	2"	4"	1"
	1"	8"	1"
	1/2"	16"	1"



CED-M/C-14

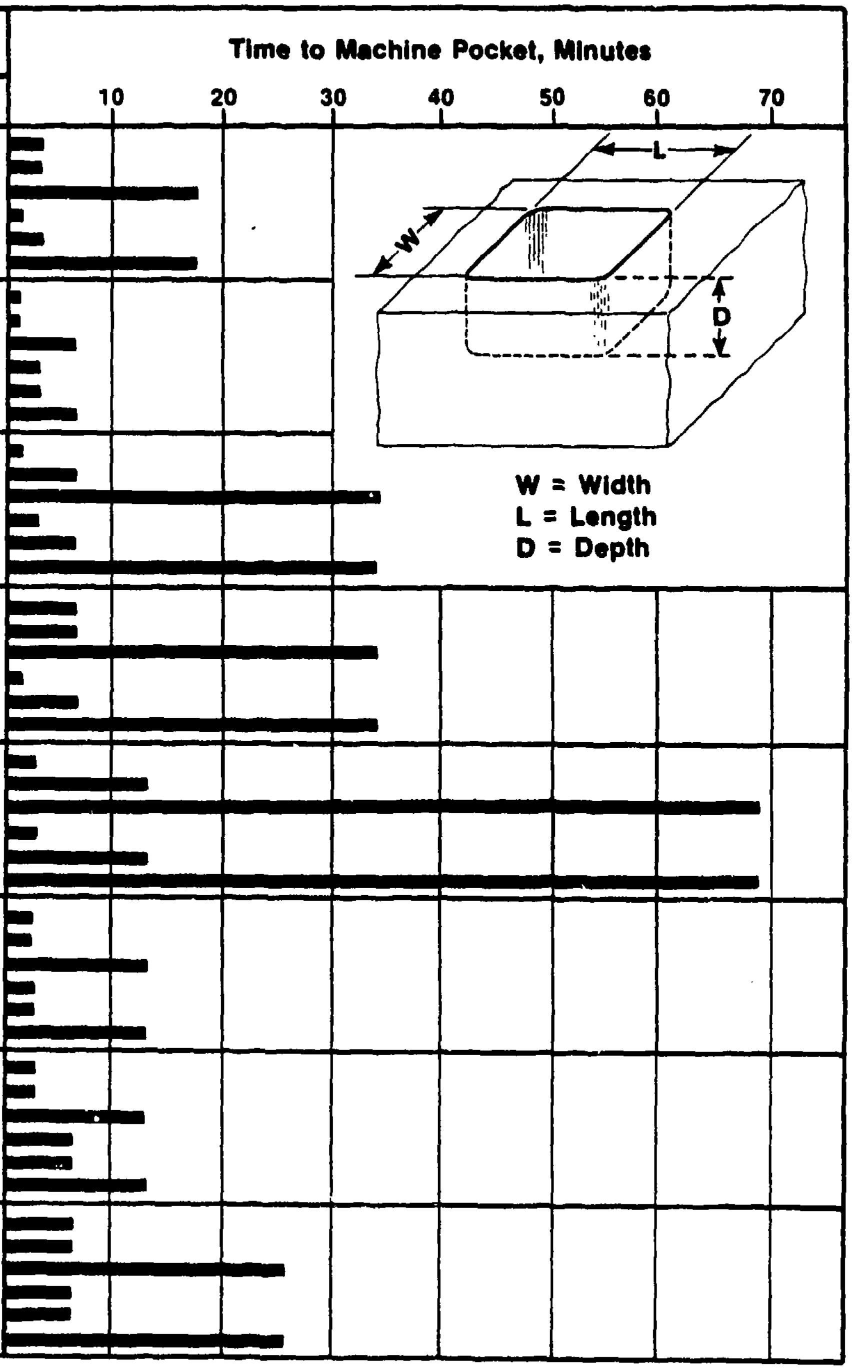
EFFECT OF POCKET/SLOT SIZE AND CONFIGURATION ON MACHINING TIME



HIGH STRENGTH STEELS

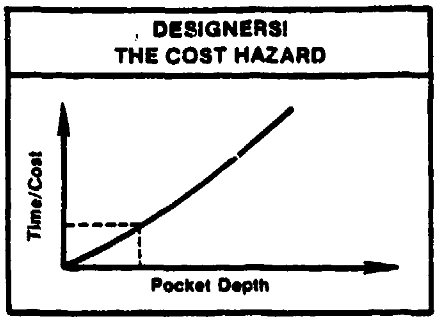
Average of Aerospace Steels

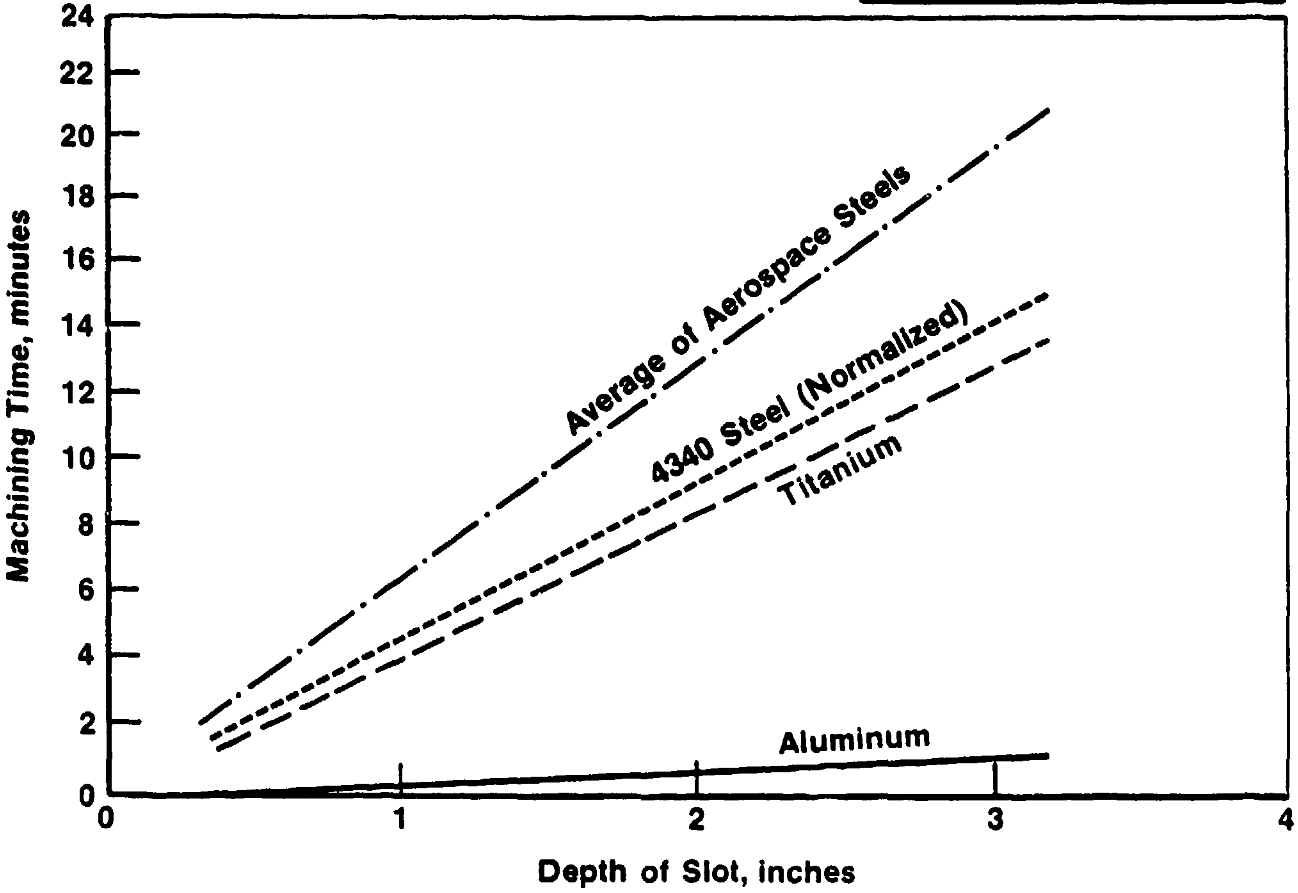
Volume of Pocket/Slot Cu. In.	Dimensions of Pocket/Slot W	L	D
1	1"	1"	1"
	1/2"	2"	1"
	1/4"	4"	1"
	1"	2"	1/2"
	1/2"	4"	1/2"
	1/4"	8"	1/2"
2 Doubling Width	2"	1"	1"
	1"	2"	1"
	1/2"	4"	1"
	2"	2"	1/2"
	1"	4"	1/2"
	1/2"	8"	1/2"
2 Doubling Length	1"	2"	1"
	1/2"	4"	1"
	1/4"	8"	1"
	1"	4"	1/2"
	1/2"	8"	1/2"
	1/4"	16"	1/2"
2 Doubling Depth	1"	1"	2"
	1/2"	2"	2"
	1/4"	4"	2"
	1"	2"	1"
	1/2"	4"	1"
	1/4"	8"	1"
4 Doubling Depth & Length	1"	2"	2"
	1/2"	4"	2"
	1/4"	8"	2"
	1"	4"	1"
	1/2"	8"	1"
	1/4"	16"	1"
4 Doubling Depth & Width	2"	1"	2"
	1"	2"	2"
	1/2"	4"	2"
	2"	2"	1"
	1"	4"	1"
	1/2"	8"	1"
4 Doubling Width & Length	2"	2"	1"
	1"	4"	1"
	1/2"	8"	1"
	2"	4"	1/2"
	1"	8"	1/2"
	1/2"	16"	1/2"
8 Doubling Width, Length & Depth	2"	2"	2"
	1"	4"	2"
	1/2"	8"	2"
	2"	4"	1"
	1"	8"	1"
	1/2"	16"	1"



CED-M/C-15

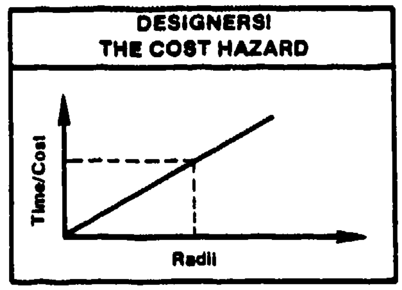
EFFECT OF DEPTH OF SLOT ON MACHINING TIME

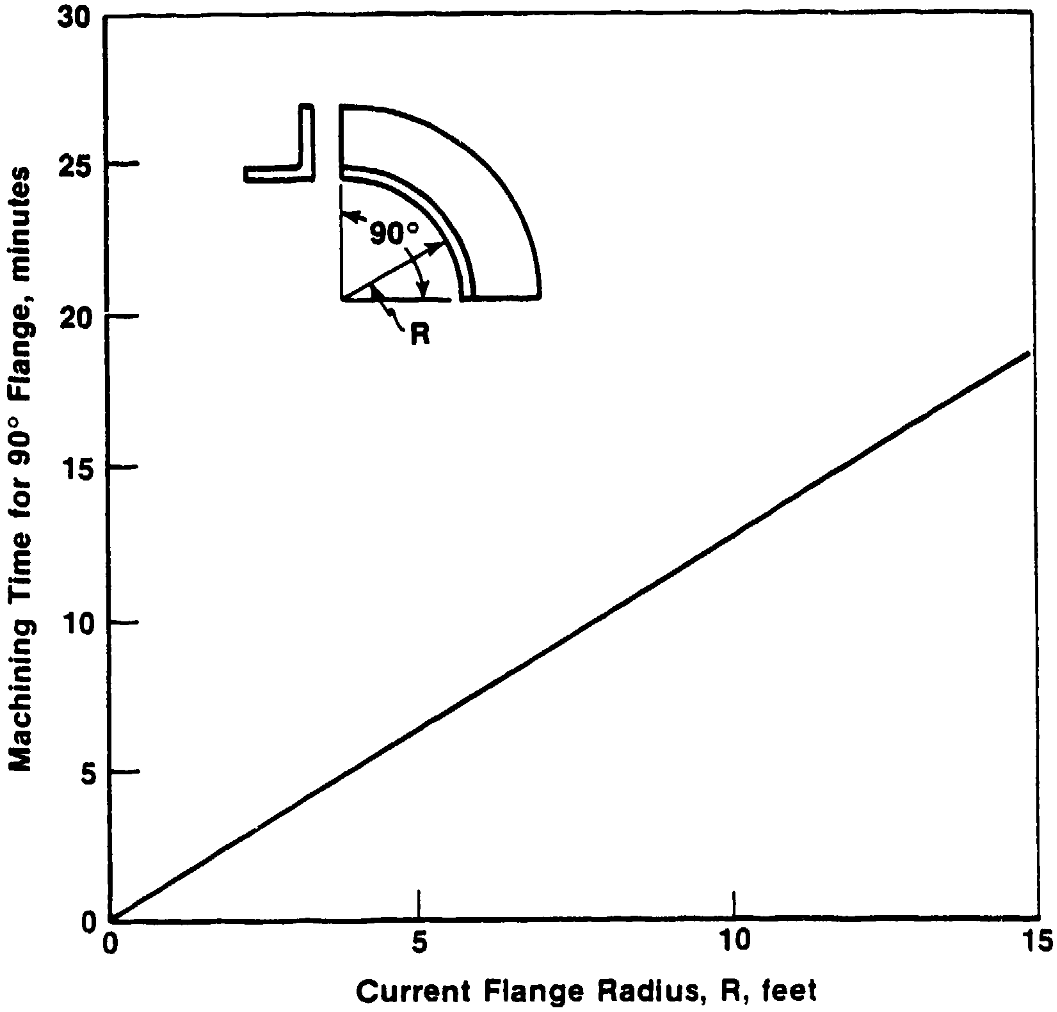




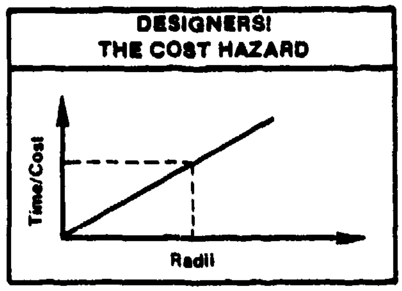
EFFECT OF CURVED FLANGE RADIUS ON MACHINING TIME FOR:

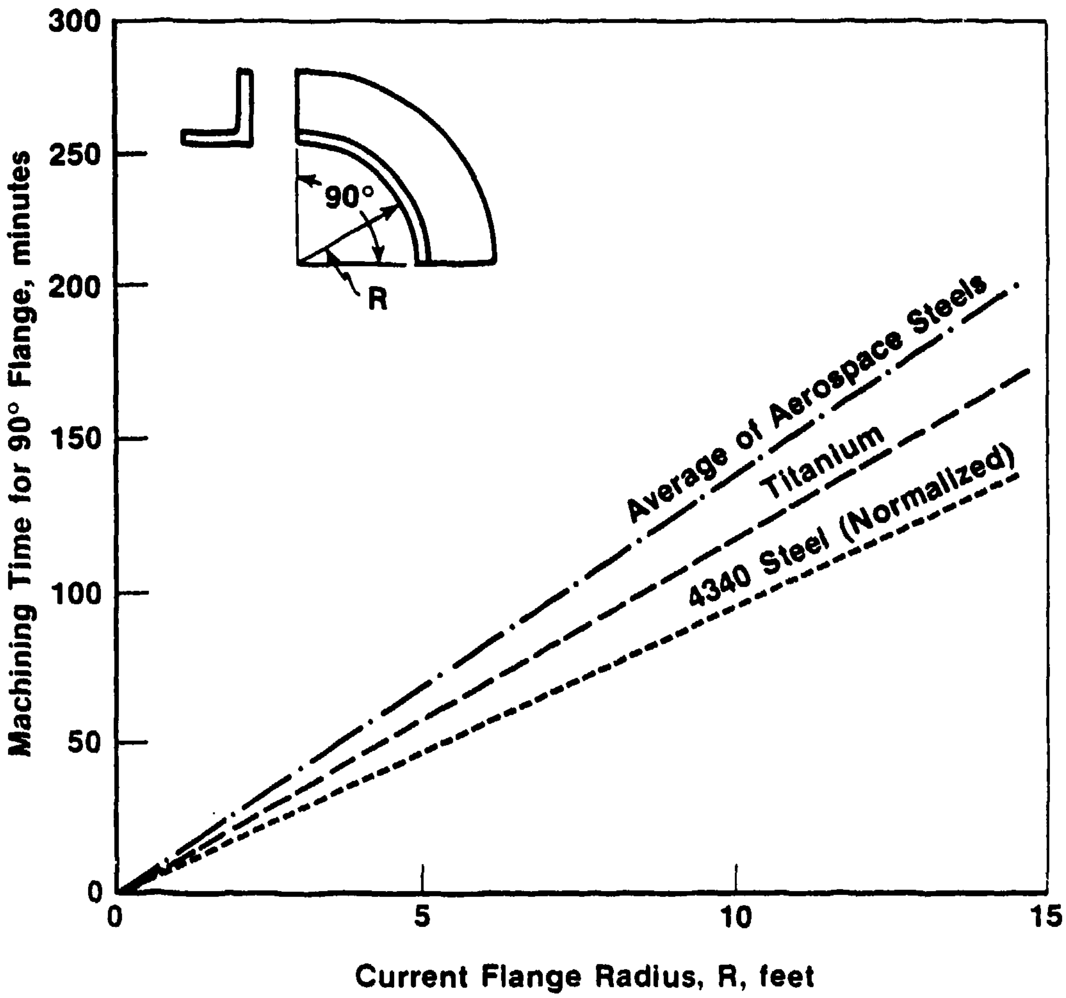
ALUMINUM





EFFECT OF CURVED FLANGE RADIUS ON MACHINING TIME FOR:
TITANIUM
HIGH STRENGTH STEELS

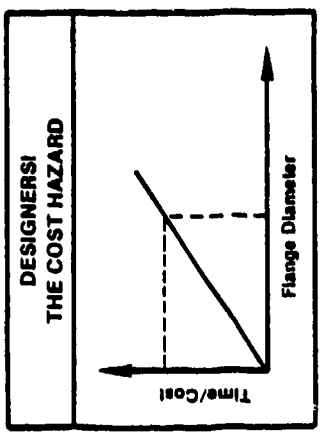


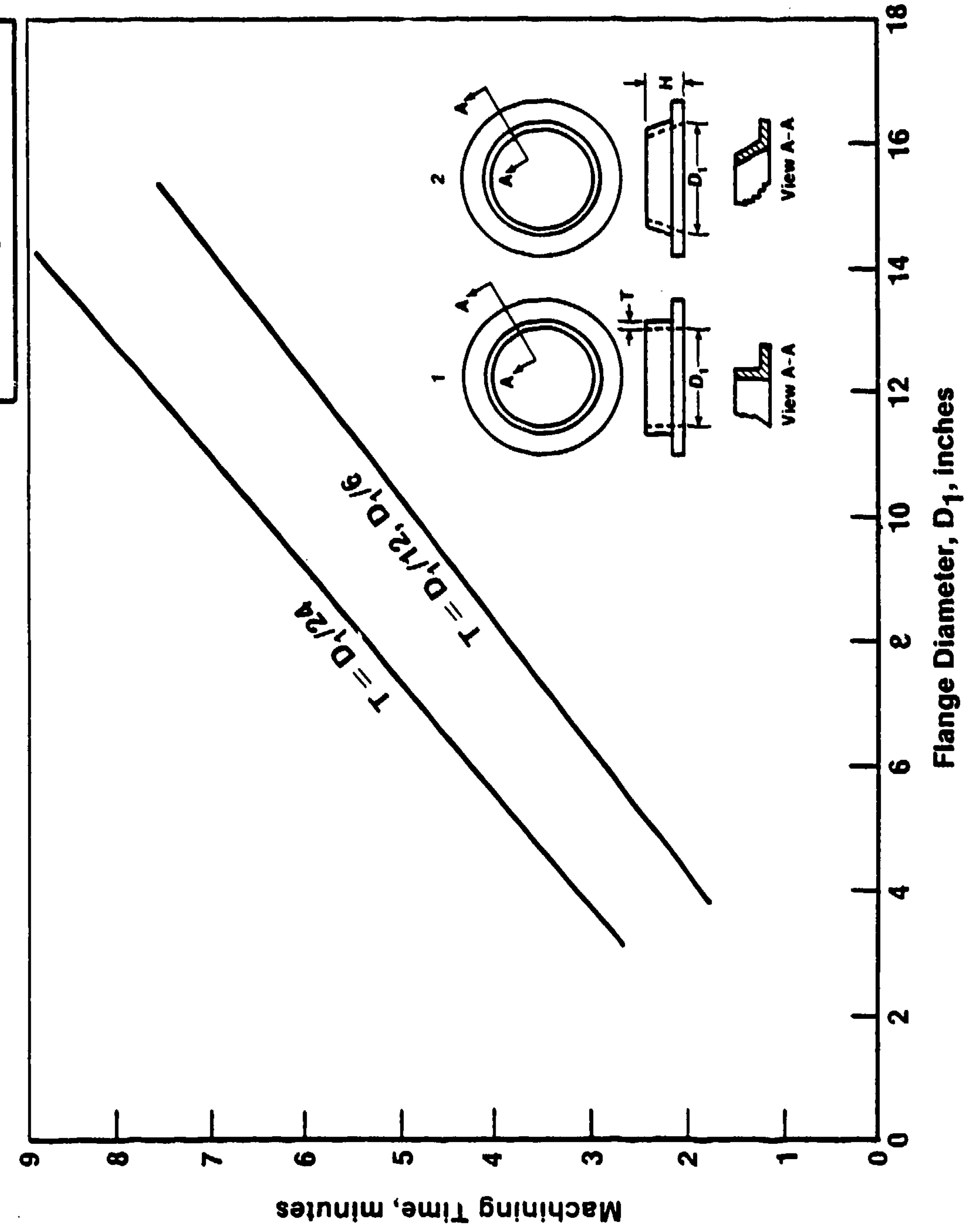


CED-M/C-18

EFFECT OF CURVED FLANGE DIAMETER FOR:

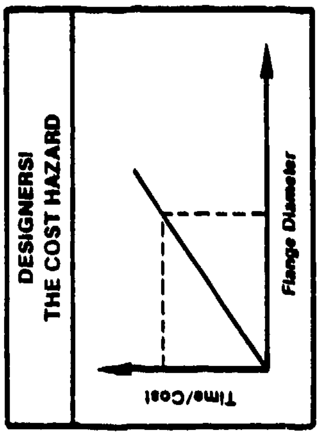
ALUMINUM

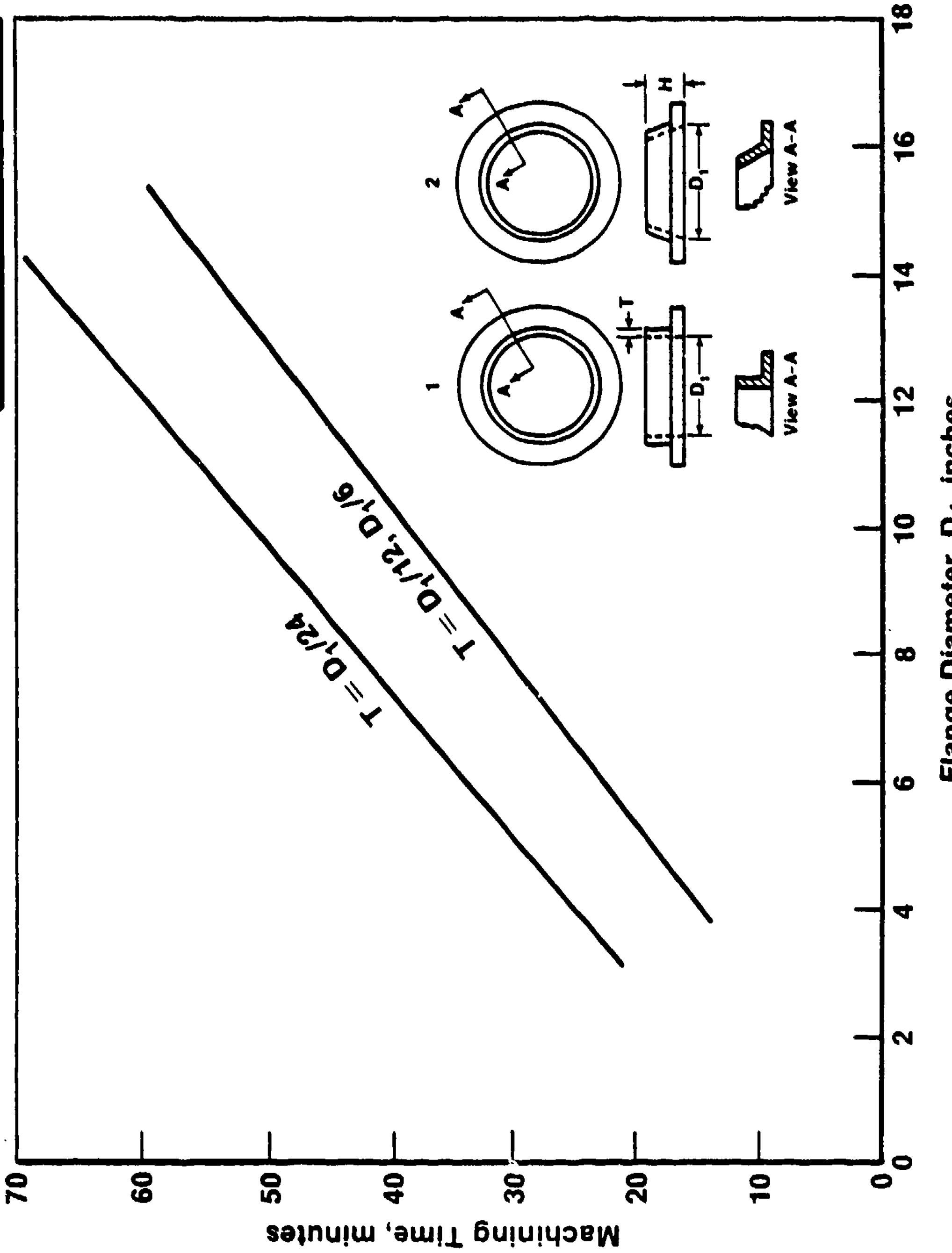




EFFECT OF CURVED FLANGE DIAMETER FOR:

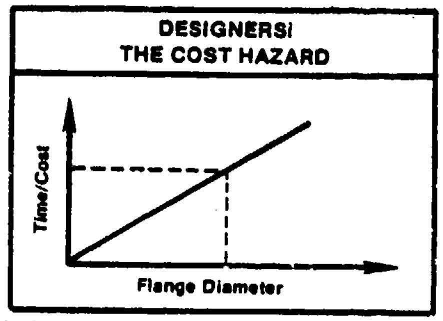
TITANIUM



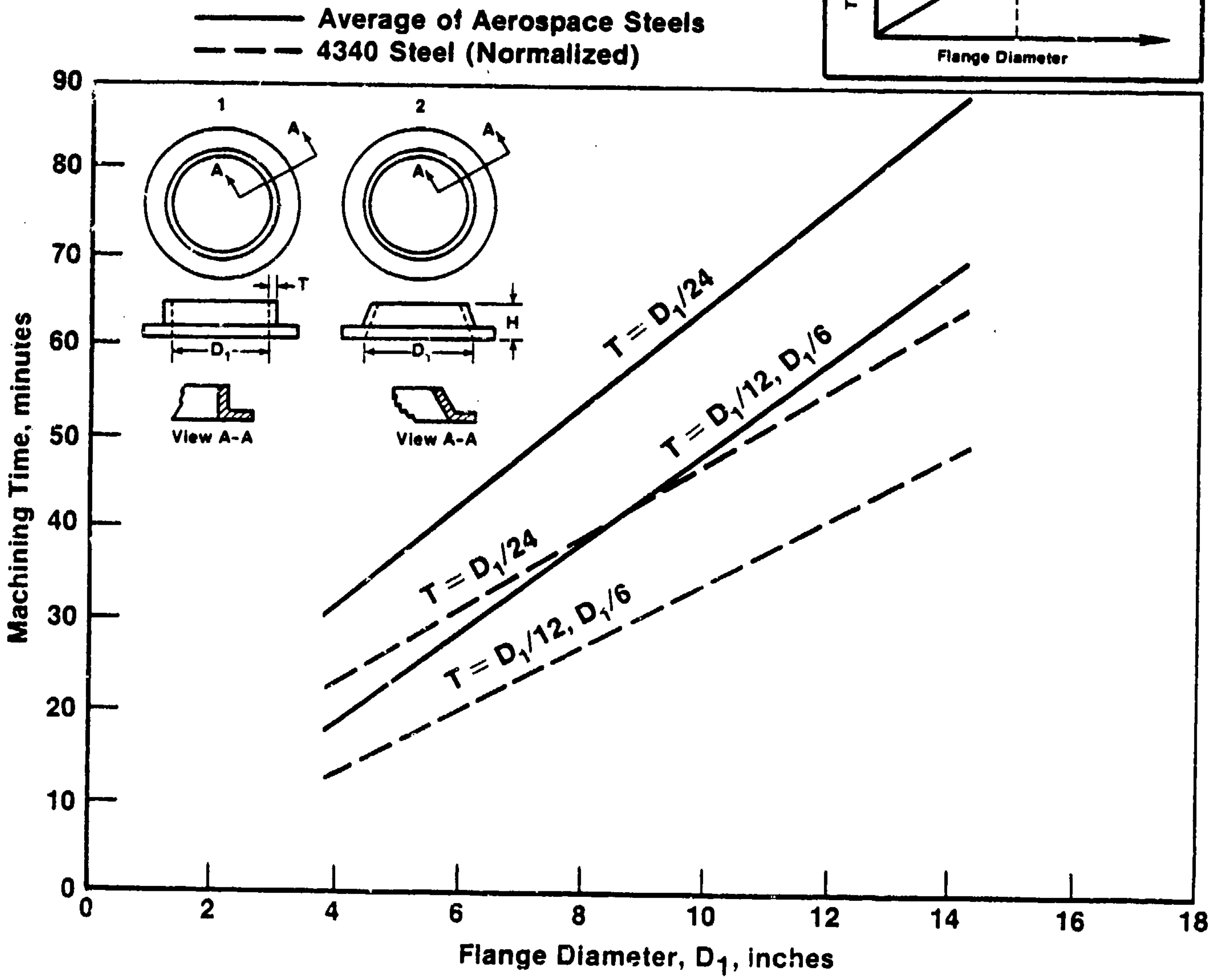


CED-M/C-20

EFFECT OF CURVED FLANGE DIAMETER FOR:

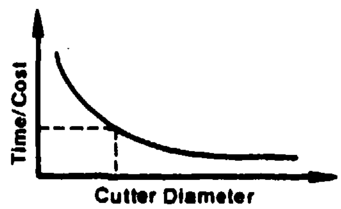


HIGH STRENGTH STEELS



EFFECT OF END-MILL DIAMETER ON MACHINING TIME

DESIGNERS! THE COST HAZARD



ALUMINUM

Diameter	Time, Minutes
1-1/2"	0.11
1"	0.11
3/4"	0.12
1/2"	0.20
3/8"	0.20

TITANIUM

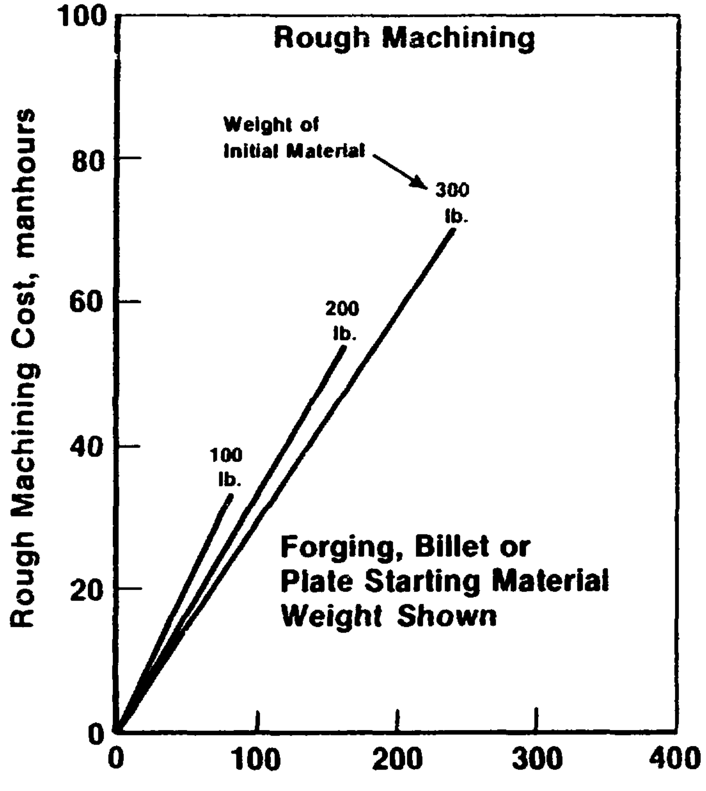
Diameter	Time, Minutes
1-1/2"	1.54
1"	1.54
3/4"	1.92
1/2"	3.85
3/8"	5.77

HIGH STRENGTH STEELS

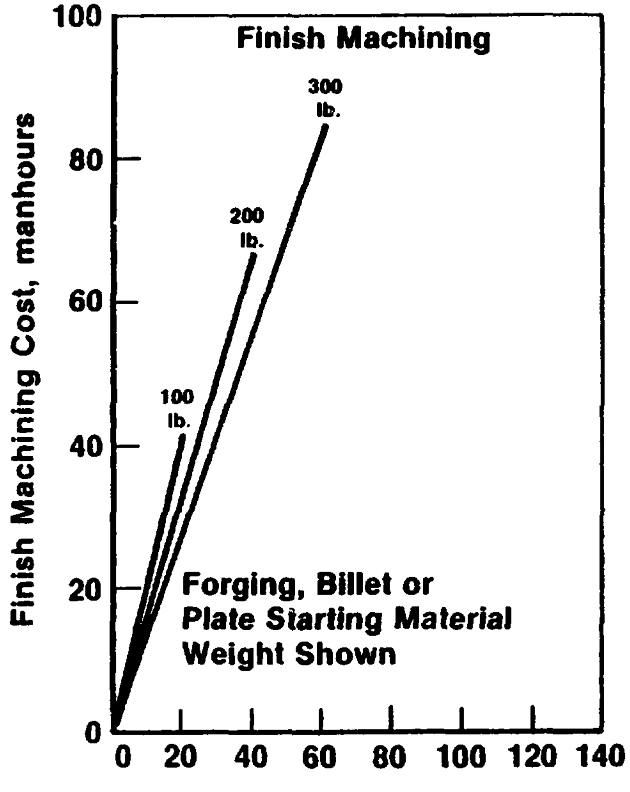
4340 Steel (Normalized)
Average of Aerospace Steels

Diameter	Time, Minutes
1-1/2"	10.20
1"	10.20
3/4"	10.20
1/2"	15.07
3/8"	16.61

RECURRING COST FOR END MILLING TITANIUM (6Al-4V Annealed) 200TH PART



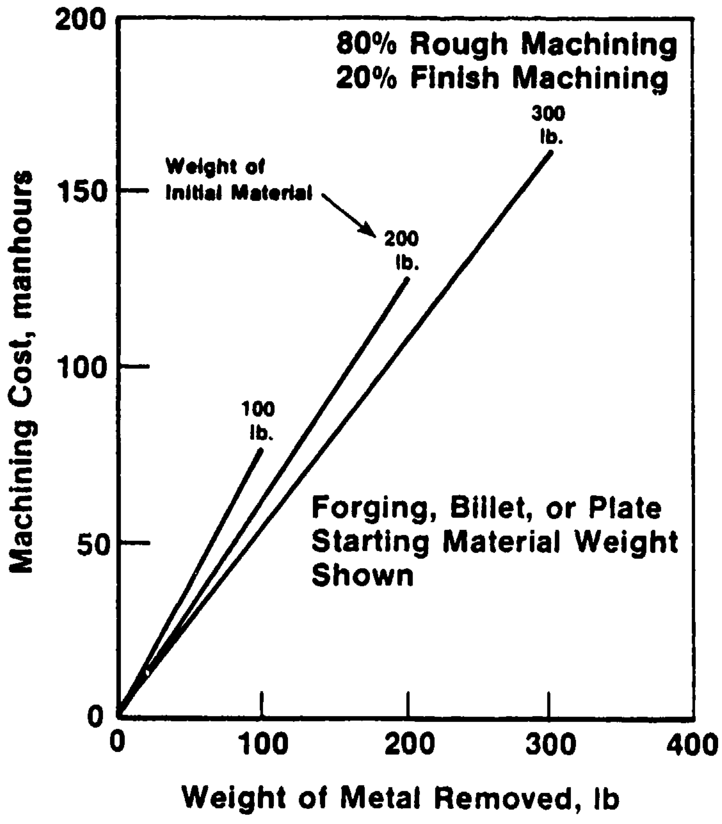
Rough Machining



Finish Machining

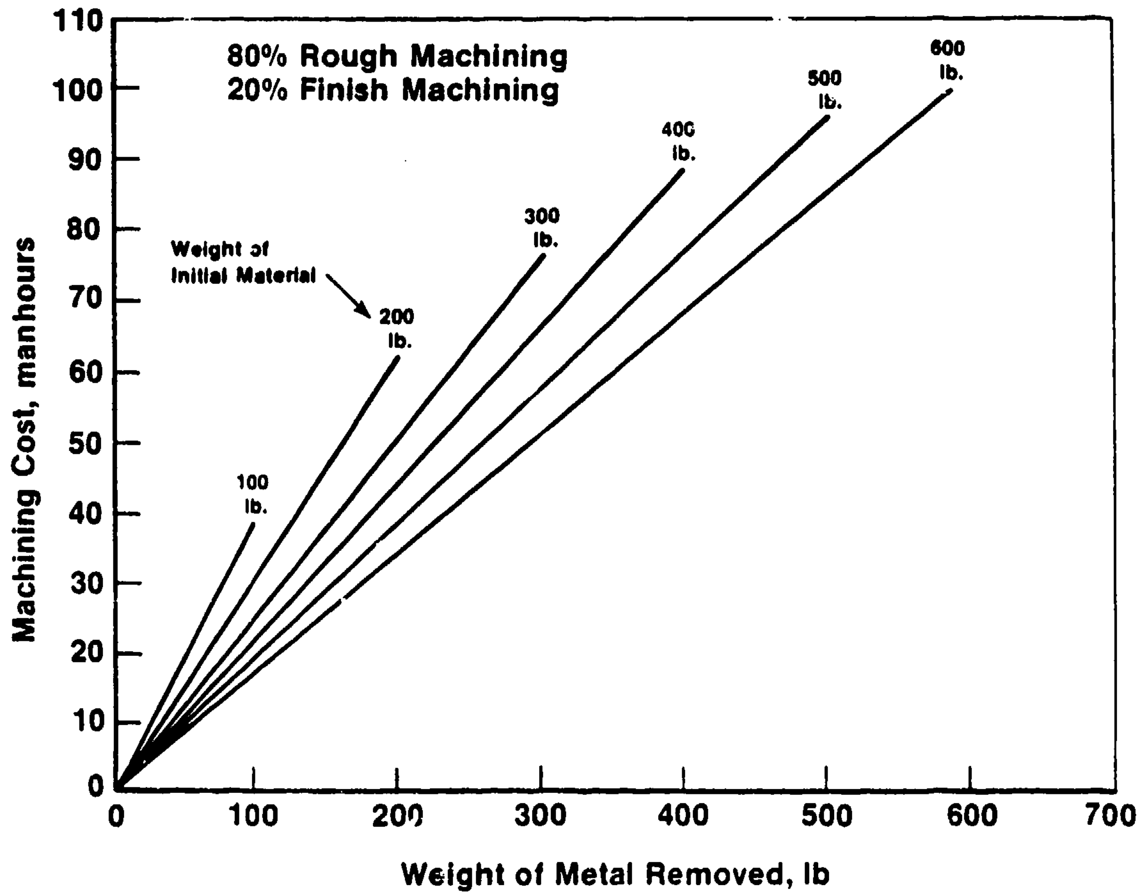
Courtesy of Lockheed-California Company

RECURRING COST FOR END MILLING TITANIUM (6Al-4V ANNEALED) 200TH PART



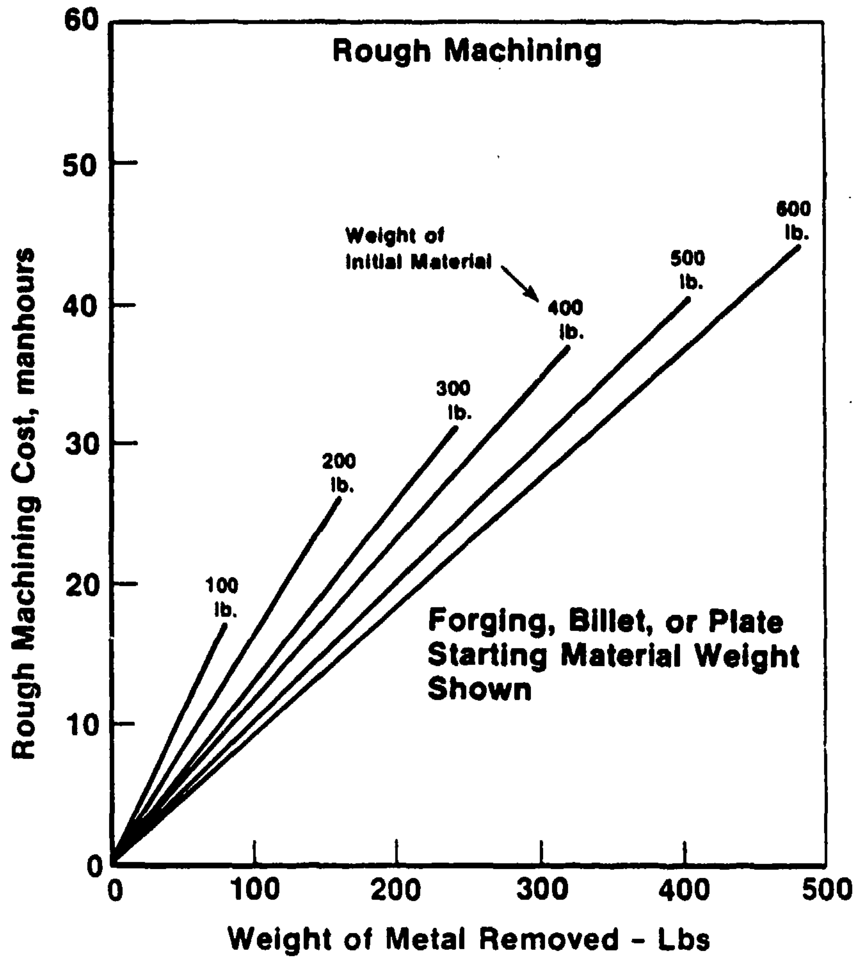
Courtesy of Lockheed-California Company

RECURRING COST FOR END MILLING ALUMINUM AT 200TH PART

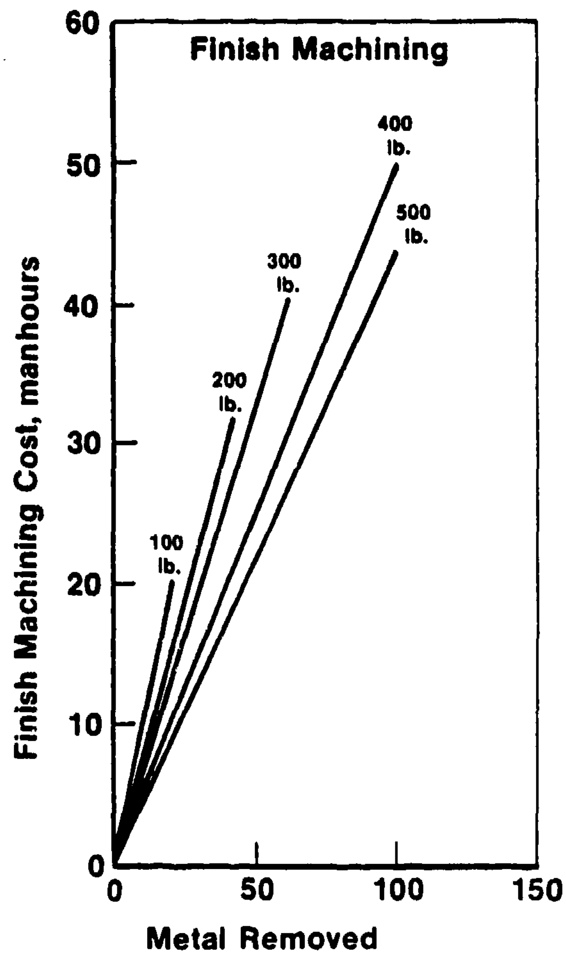


Courtesy of Lockheed-California Company

RECURRING COST FOR END MILLING ALUMINUM AT 200TH PART



Rough Machining



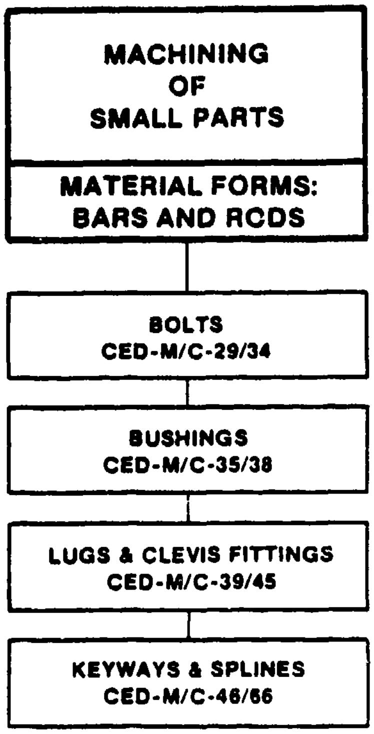
Finish Machining

Courtesy of Lockheed-California Company

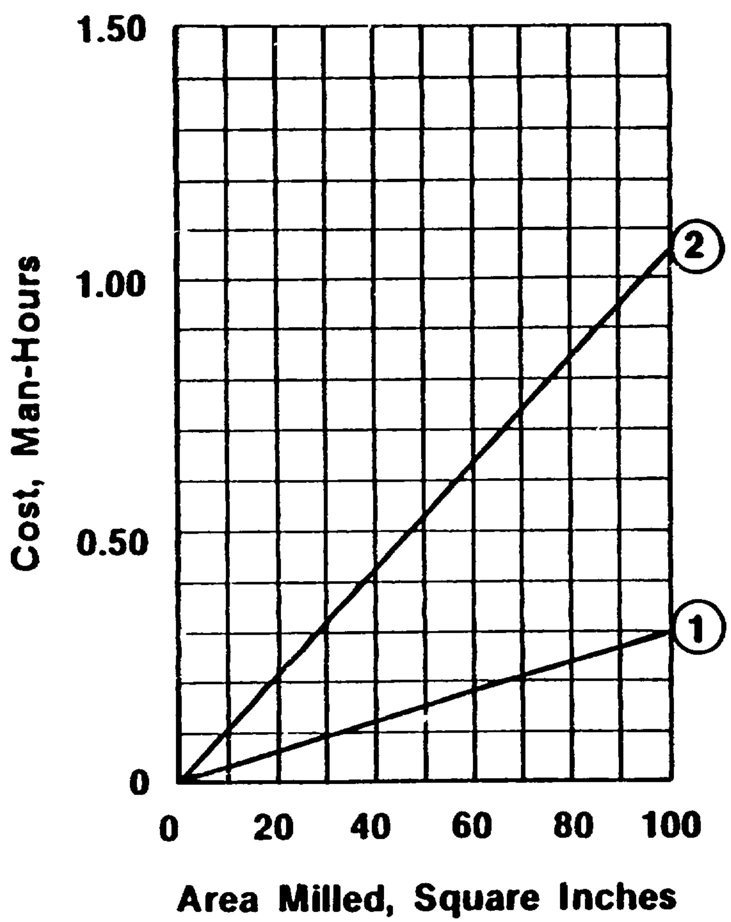
CED-M/C-26

FORMAT SELECTION AID

MACHINING OF METALS



SECONDARY MACHINING
FACE MILLING



Nonrecurring Tool Cost
NRTC = 57 Man-Hours

(1) Aluminum 356/A, 356-T6, 2024 and 7075

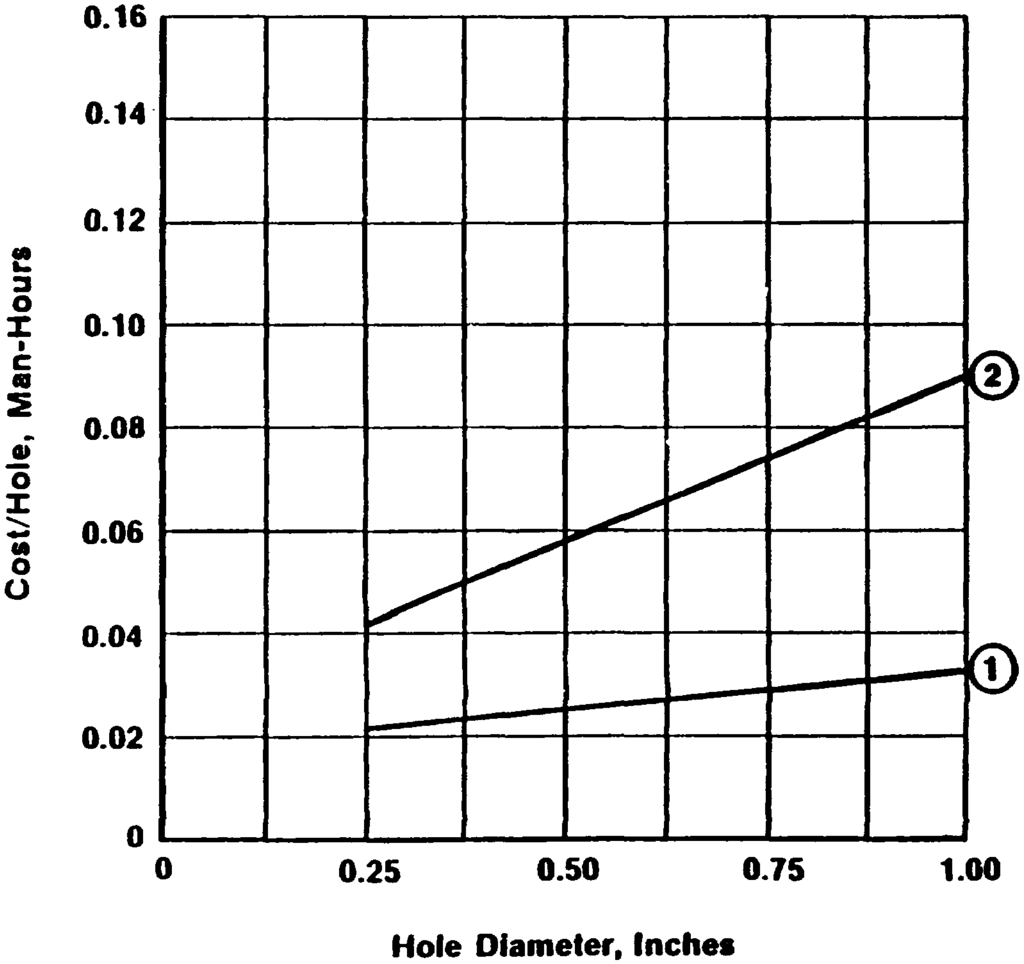
(2) Titanium 6Al-4V Annealed; Steel CRES; PH CRES, COND A 4130, 4140, 4340 Normalized

Step 1 — Determine the face milling cost for <u>each</u> surface machined.

Step 2 — Add the milling costs obtained in Step 1.

Step 3 — Obtain NRTC above.

SECONDARY MILLING
DRILL AND SPOTFACE HOLES



Nonrecurring Tool Cost

NRTC = (32 + 2N) Man-Hours

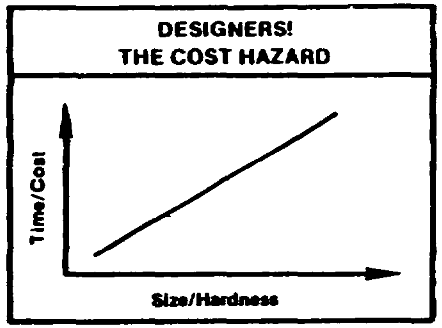
Where N is the number of holes in the pattern.

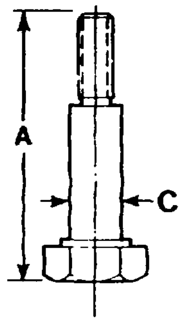
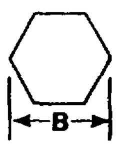
1. Aluminum 356/A, 356-T6, 2024 and 7075
2. Titanium 6Al-4V Annealed; Steel CRES; PH CRES, COND A 4130, 4140, 4340 Normalized

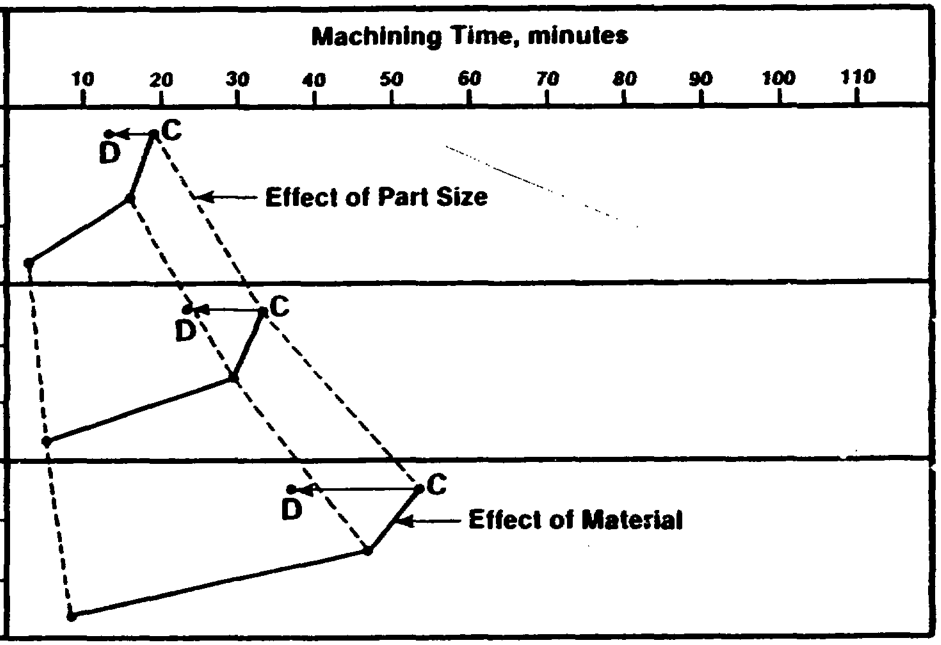
Cost/Part = (Cost/Hole • N) Man-Hours

Cost data is valid for hole depths up to twice the hole diameter.

EFFECT OF SIZE AND MATERIAL ON MACHINING TIME FOR TURNED PARTS

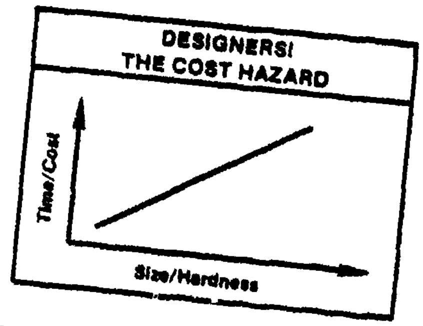


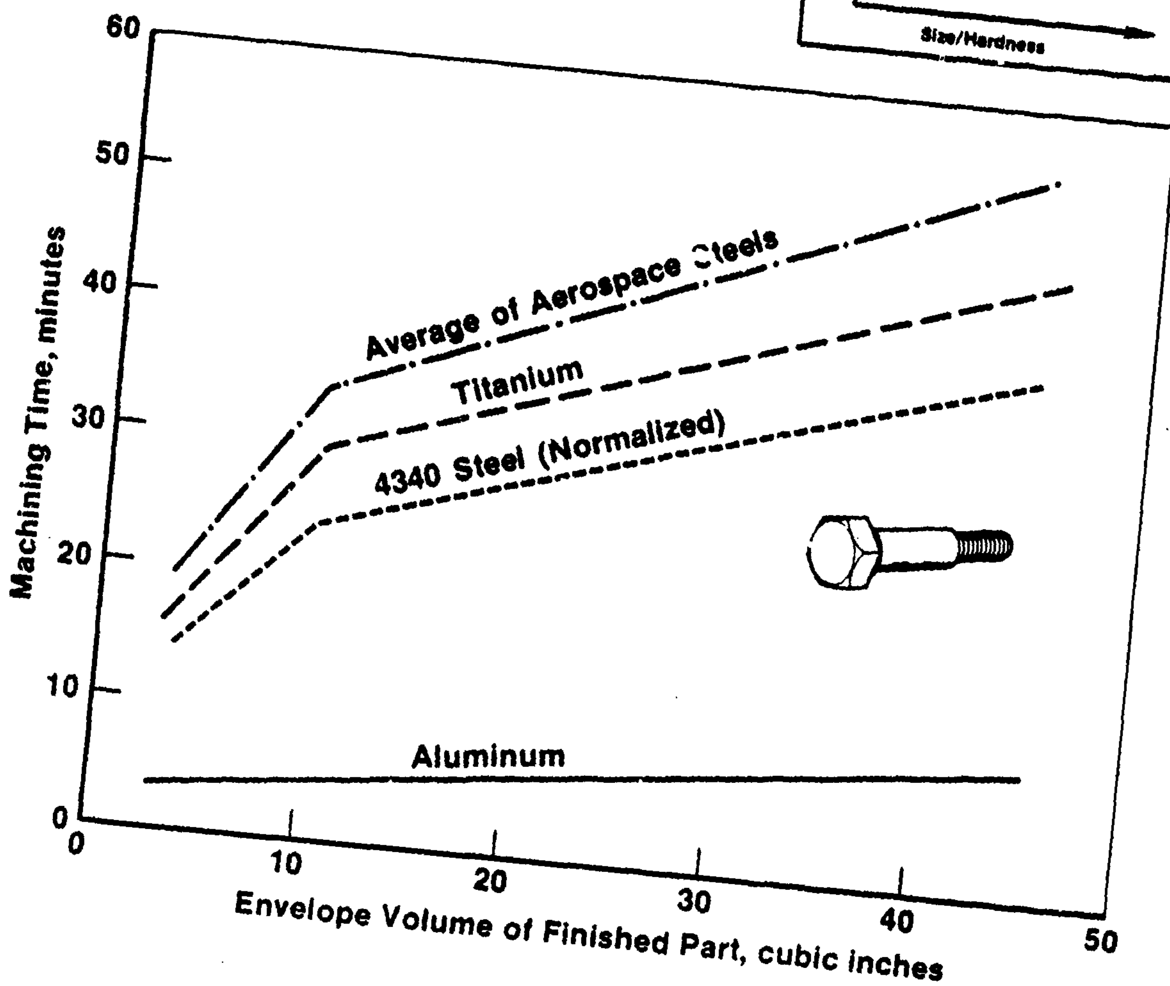
Part Type	Dimension, inches			Material
	A	B	C	
	3.75	1.125	0.750	Steel
				Titanium
				Aluminum
	7.00	1.875	1.250	Steel
				Titanium
				Aluminum
	11.25	3.000	2.000	Steel
				Titanium
				Aluminum



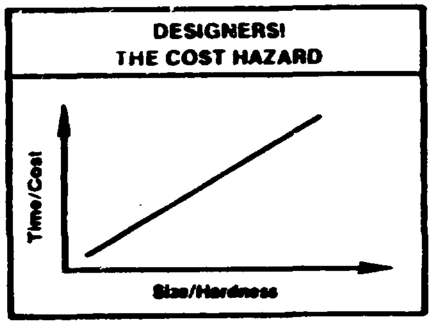
C: Average of Aerospace Steels
D: 4340 Steel (Normalized)

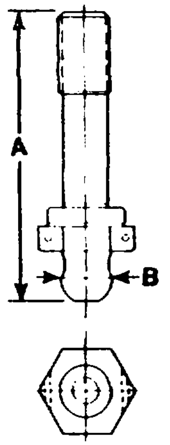
EFFECT OF SIZE AND MATERIAL ON MACHINING TIME FOR TURNED PARTS

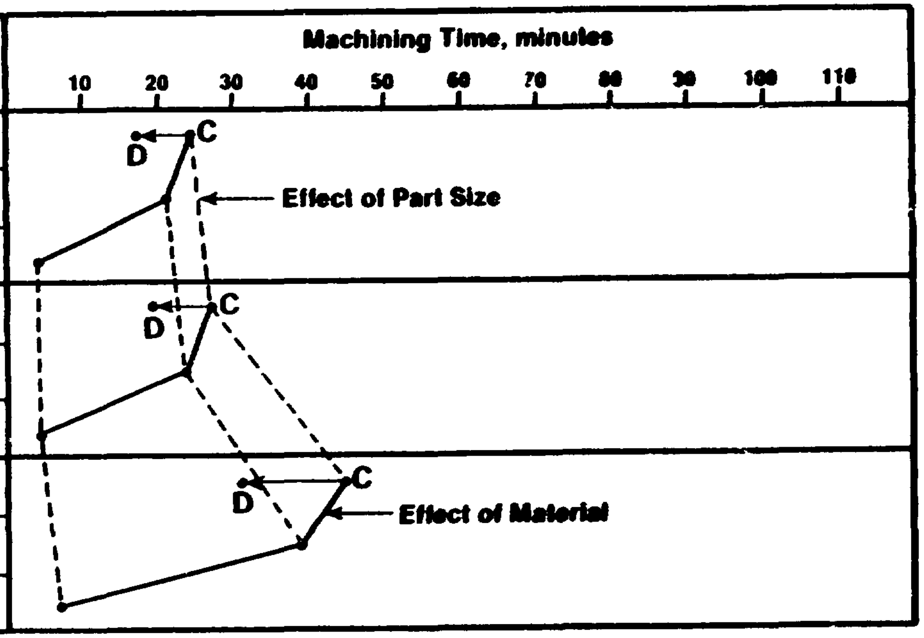




EFFECT OF SIZE AND MATERIAL ON MACHINING TIME FOR TURNED PARTS

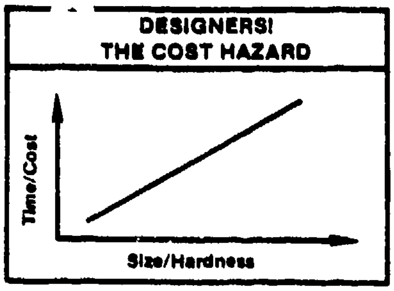


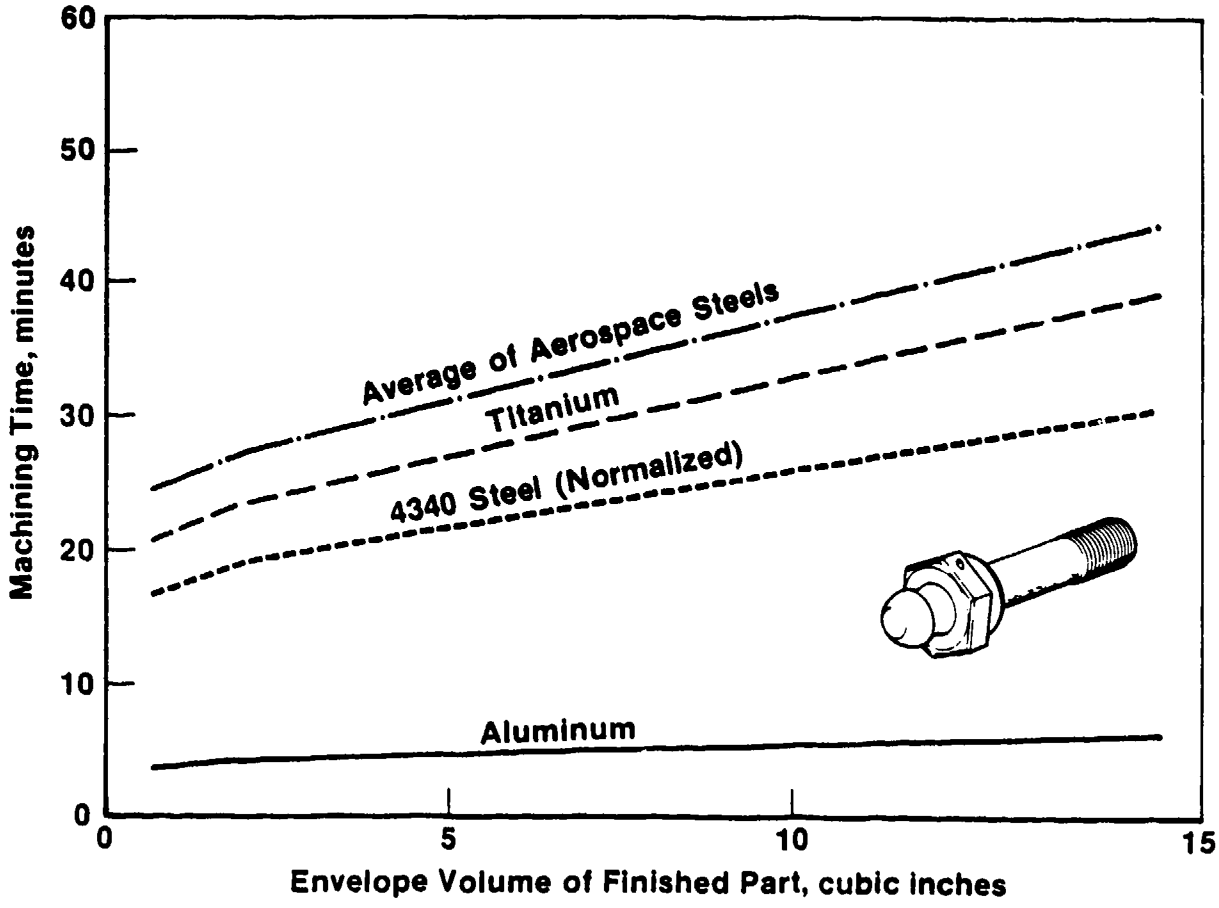
Part Type	Dimension, inches A	Dimension, inches B	Material
	4.0	0.50	Steel
			Titanium
			Aluminum
	5.0	0.75	Steel
			Titanium
			Aluminum
	8.0	1.50	Steel
			Titanium
			Aluminum



C: Average of Aerospace Steels
D: 4340 Steel (Normalized)

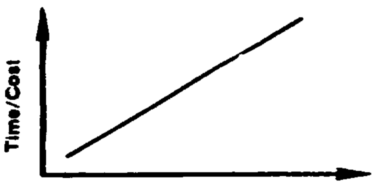
EFFECT OF SIZE AND MATERIAL ON MACHINING TIME FOR TURNED PARTS

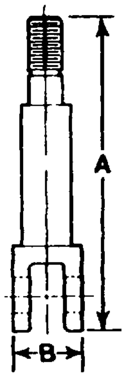




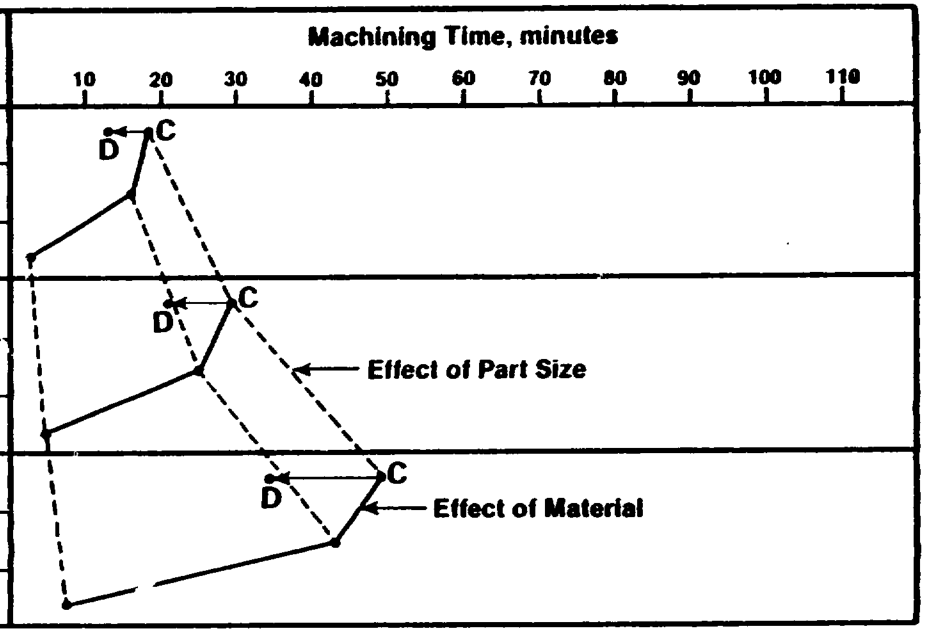
EFFECT OF SIZE AND MATERIAL ON MACHINING TIME OF FITTINGS

DESIGNERS!
THE COST HAZARD



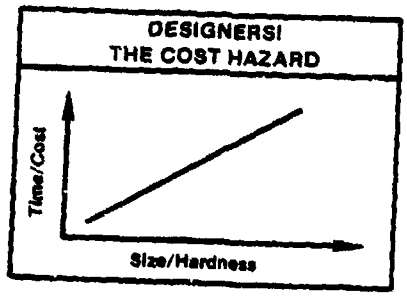


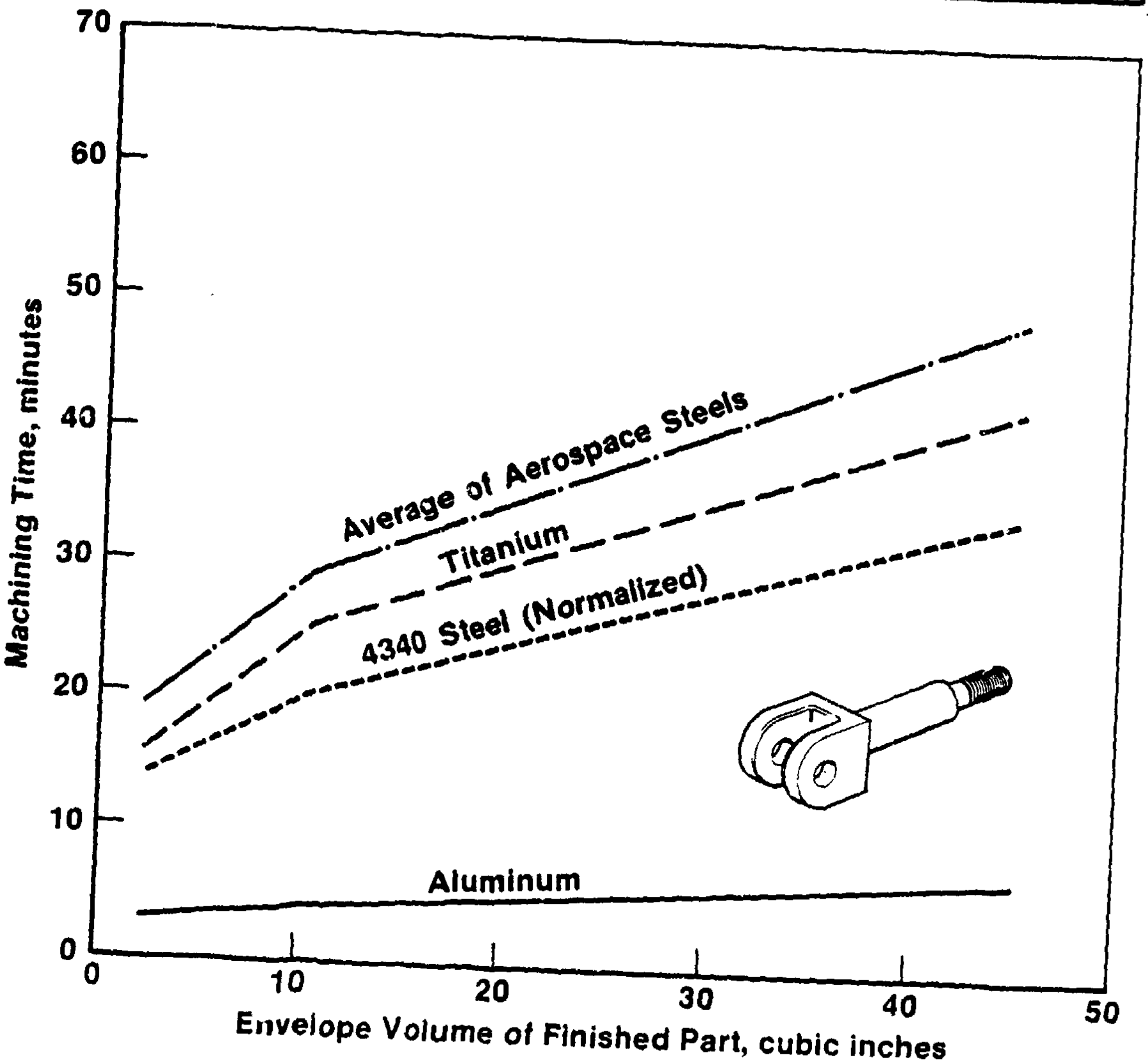
Part Type	Dimension, inches A	Dimension, inches B	Material
	4.5	0.750	Steel
			Titanium
			Aluminum
	8.4	1.250	Steel
			Titanium
			Aluminum
	13.8	2.000	Steel
			Titanium
			Aluminum



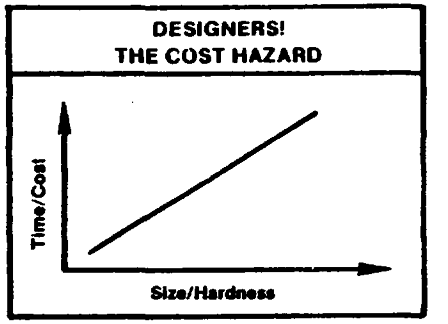
C: Average of Aerospace Steels
D: 4340 Steel (Normalized)

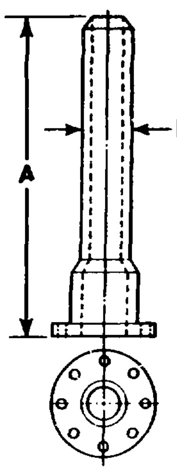
EFFECT OF SIZE AND MATERIAL ON MACHINING TIME OF FITTINGS

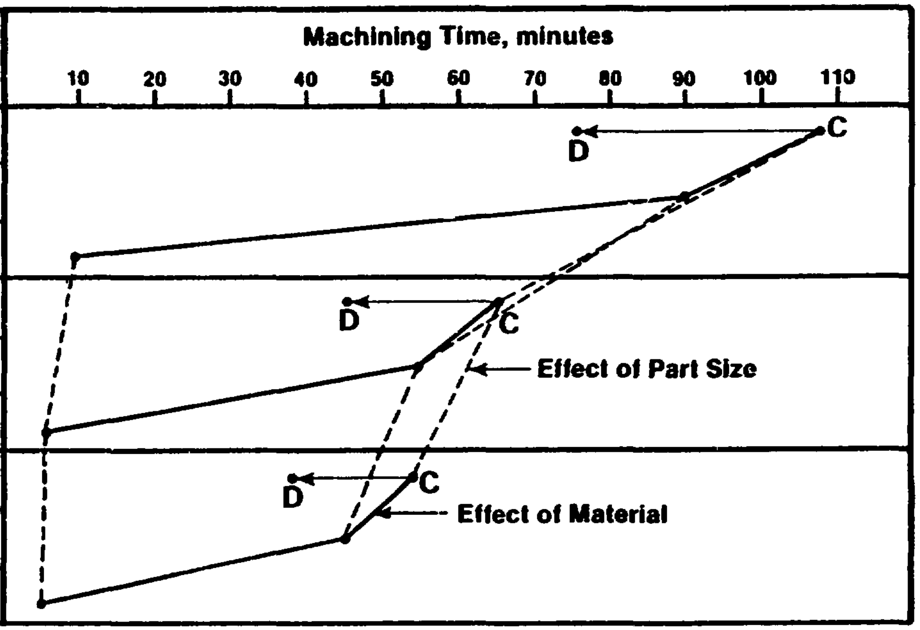




EFFECT OF SIZE AND MATERIAL ON MACHINING TIME FOR TURNED PARTS



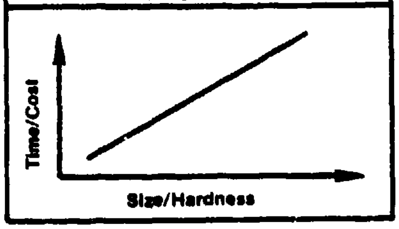
Part Type	Dimension, inches A	Dimension, inches B	Material
	16.0	3.000	Steel
			Titanium
			Aluminum
	12.0	2.125	Steel
			Titanium
			Aluminum
	8.0	1.750	Steel
			Titanium
			Aluminum

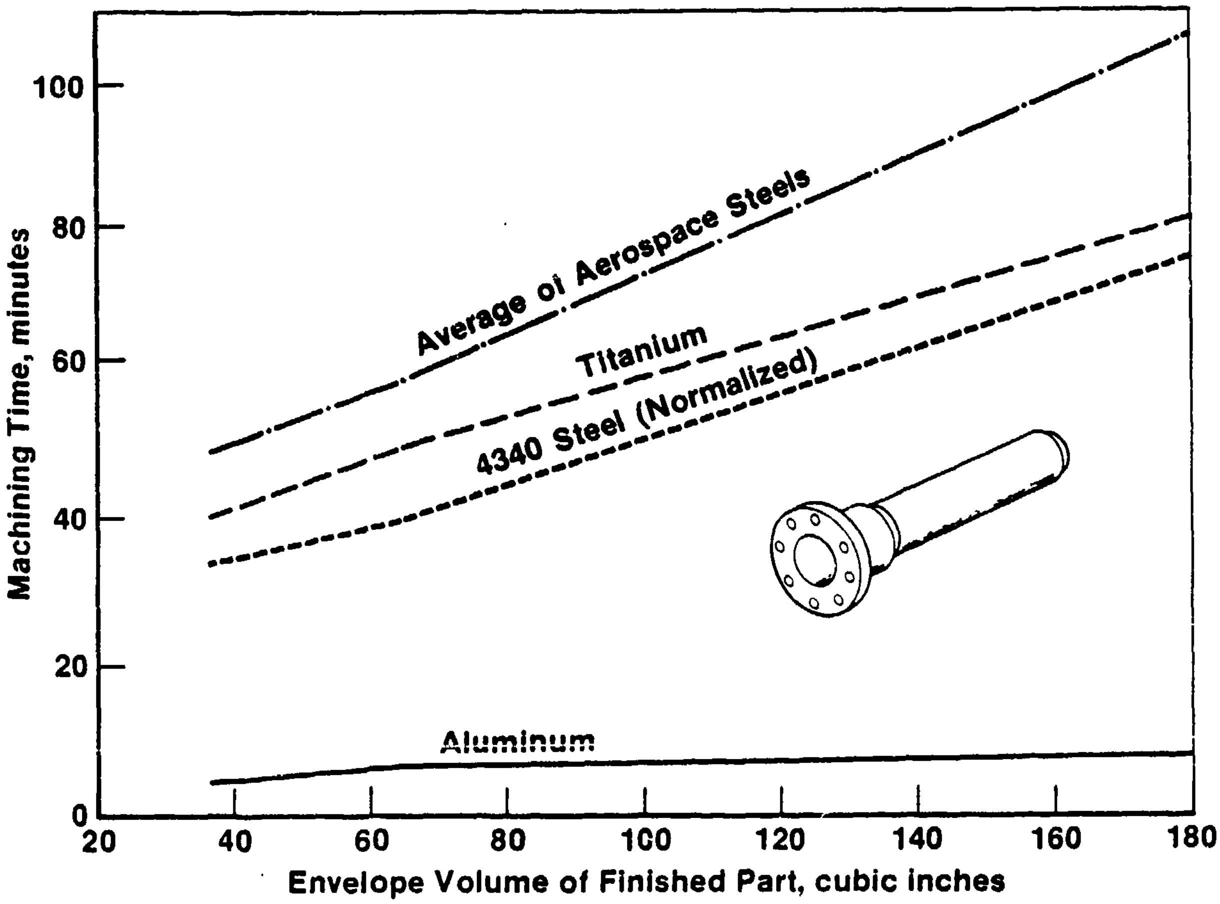


C: Average of Aerospace Steels
D: 4340 Steel (Normalized)

EFFECT OF SIZE AND MATERIAL ON MACHINING TIME FOR TURNED PARTS

DESIGNERS!
THE COST HAZARD





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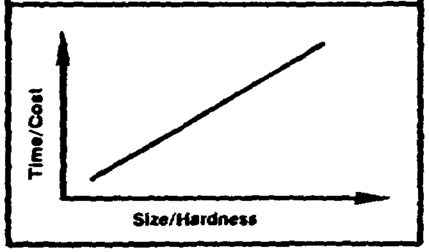
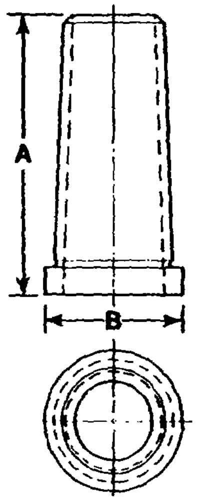
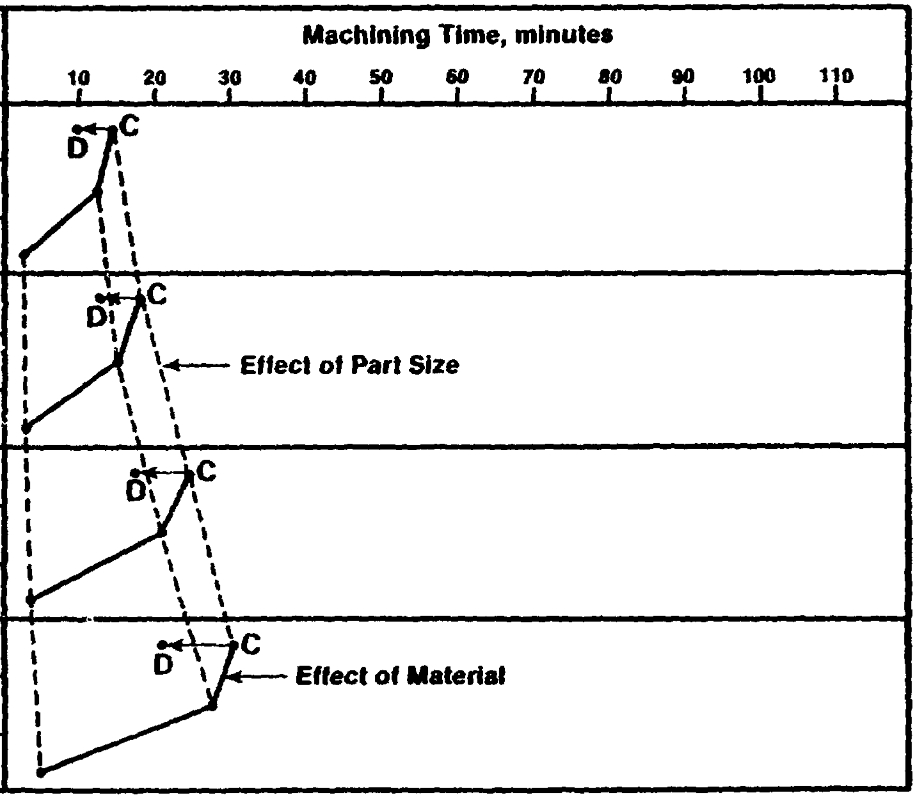
EFFECT OF SIZE AND MATERIAL ON MACHINING TIME FOR TURNED PARTS



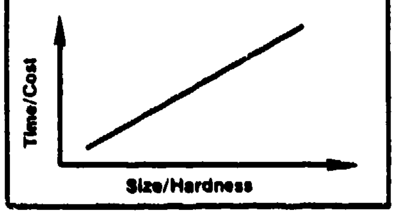
Part Type	Dimension, inches A	Dimension, inches B	Material
	4.0	2.0	Steel
			Titanium
			Aluminum
	6.0	3.0	Steel
			Titanium
			Aluminum
	8.0	4.0	Steel
			Titanium
			Aluminum
	10.0	5.0	Steel
			Titanium
			Aluminum

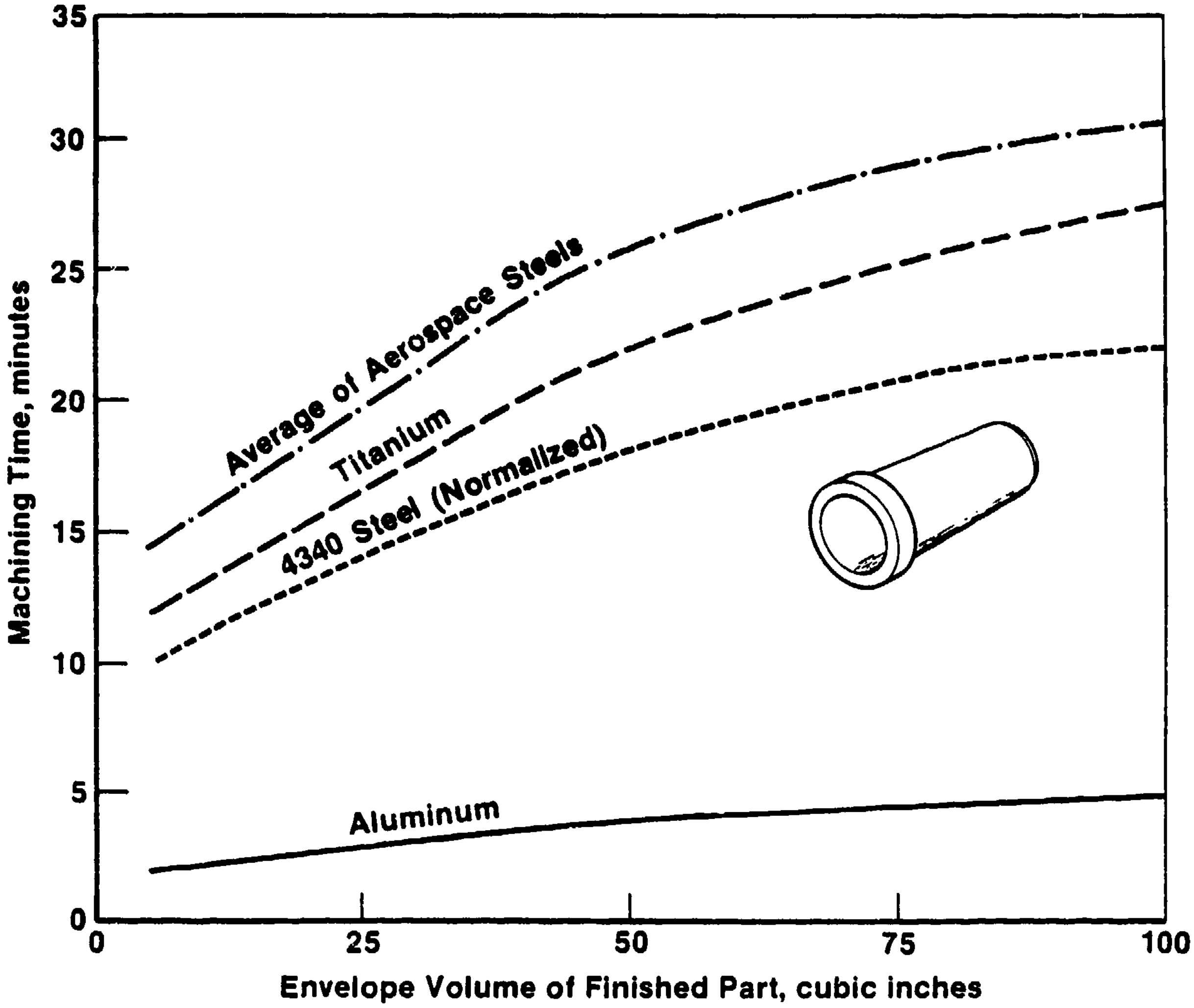


C: Average of Aerospace Steels
D: 4340 Steel (Normalized)

EFFECT OF SIZE AND MATERIAL ON MACHINING TIME FOR TURNED PARTS

DESIGNERS!
THE COST HAZARD





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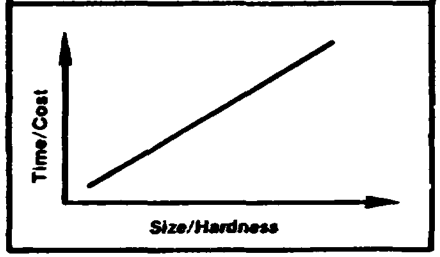
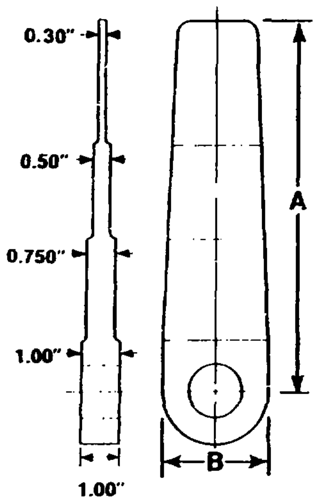
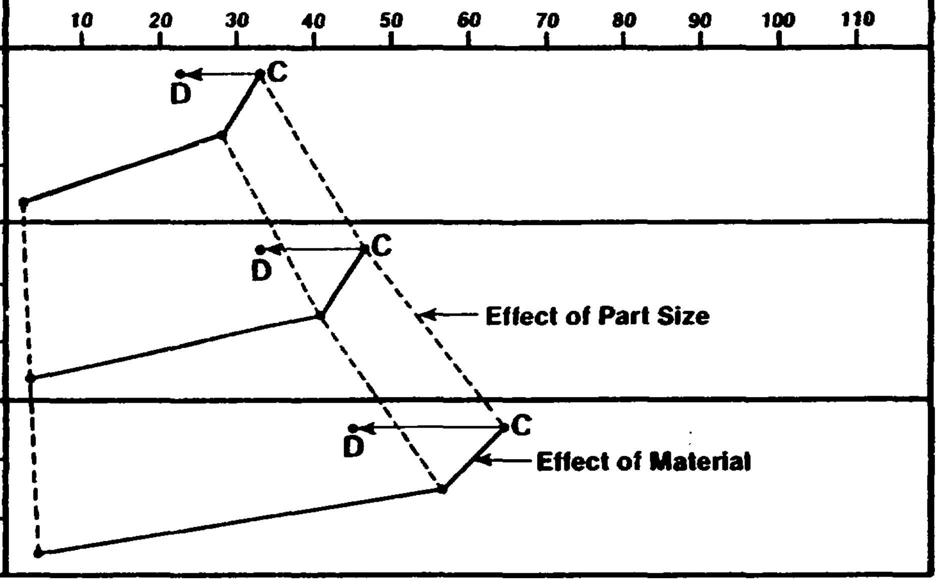
EFFECT OF SIZE AND MATERIAL ON MACHINING TIME OF FITTINGS

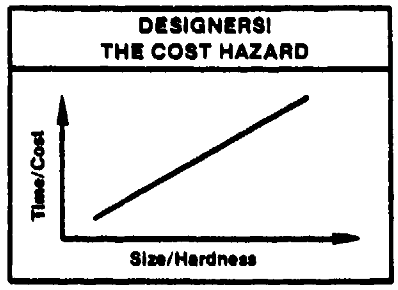
DESIGNERS!
THE COST HAZARD

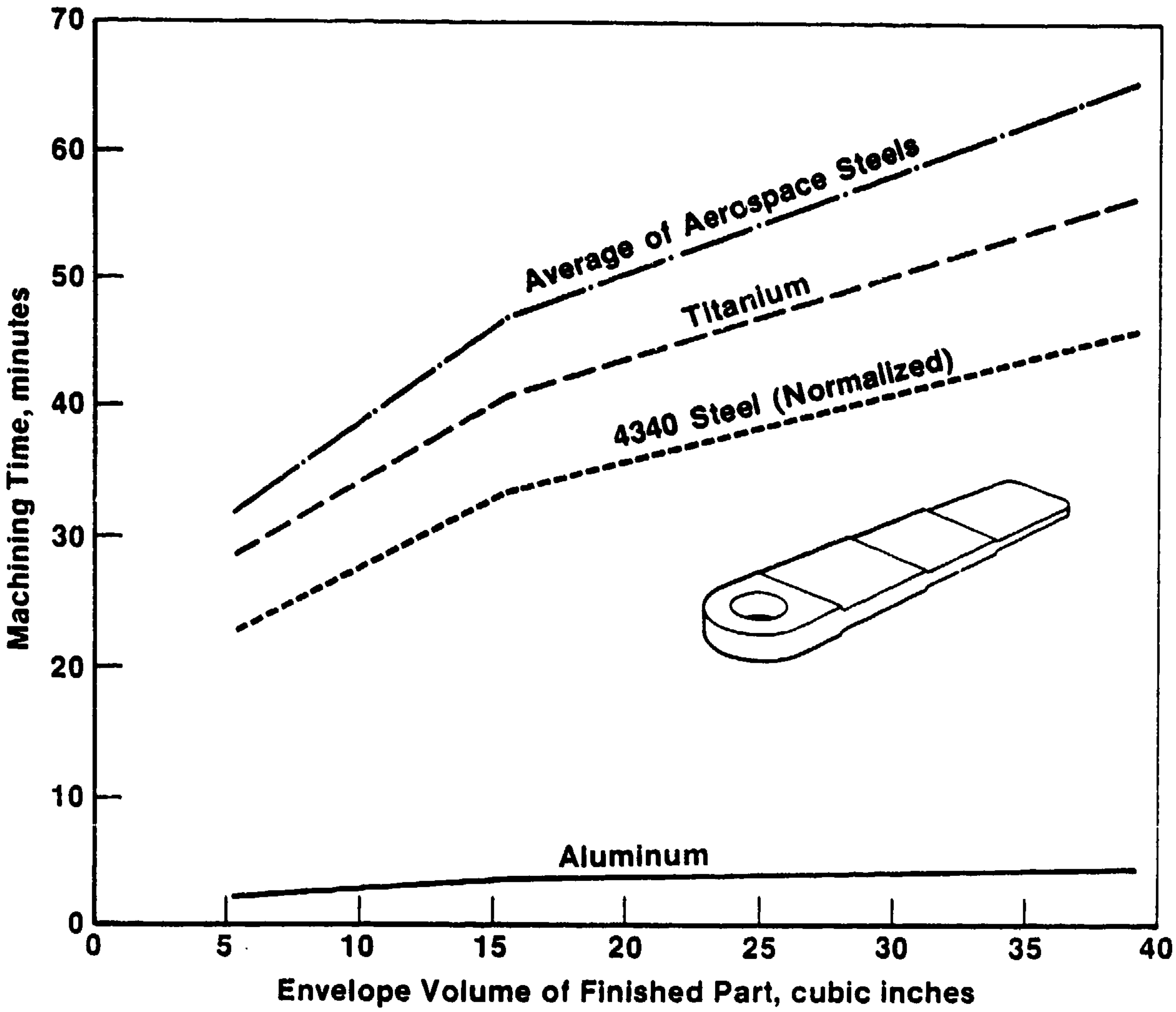


Part Type	Dimension, inches A	Dimension, inches B	Material	Machining Time, minutes
	9.0	1.0	Steel	
			Titanium	
			Aluminum	
	12.0	1.5	Steel	
			Titanium	
			Aluminum	
	16.0	2.0	Steel	
			Titanium	
			Aluminum	

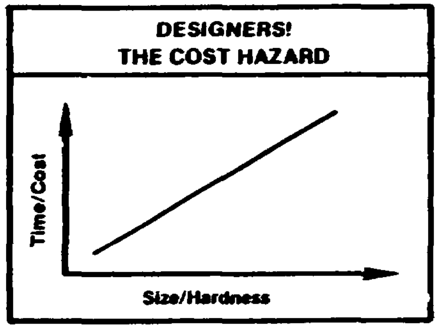
C: Average of Aerospace Steels
D: 4340 Steel (Normalized)

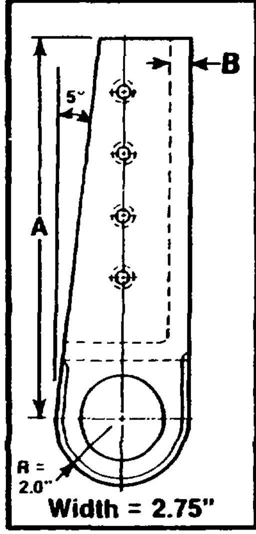
EFFECT OF SIZE AND MATERIAL ON MACHINING TIME OF FITTINGS

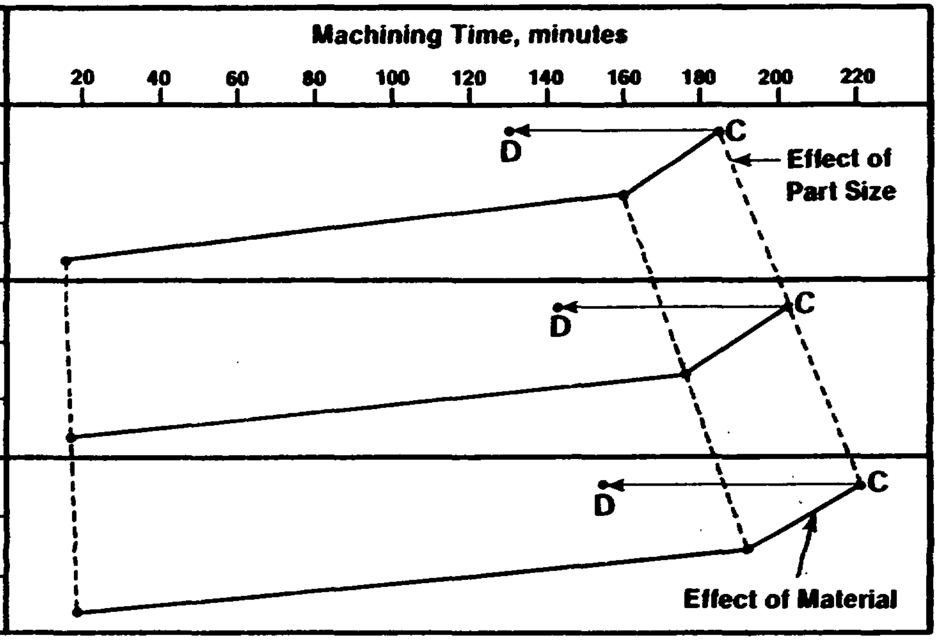




EFFECT OF SIZE AND MATERIAL ON MACHINING TIME OF FITTINGS

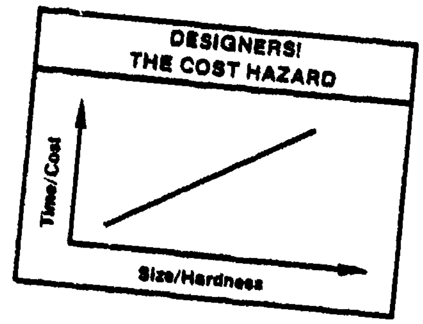


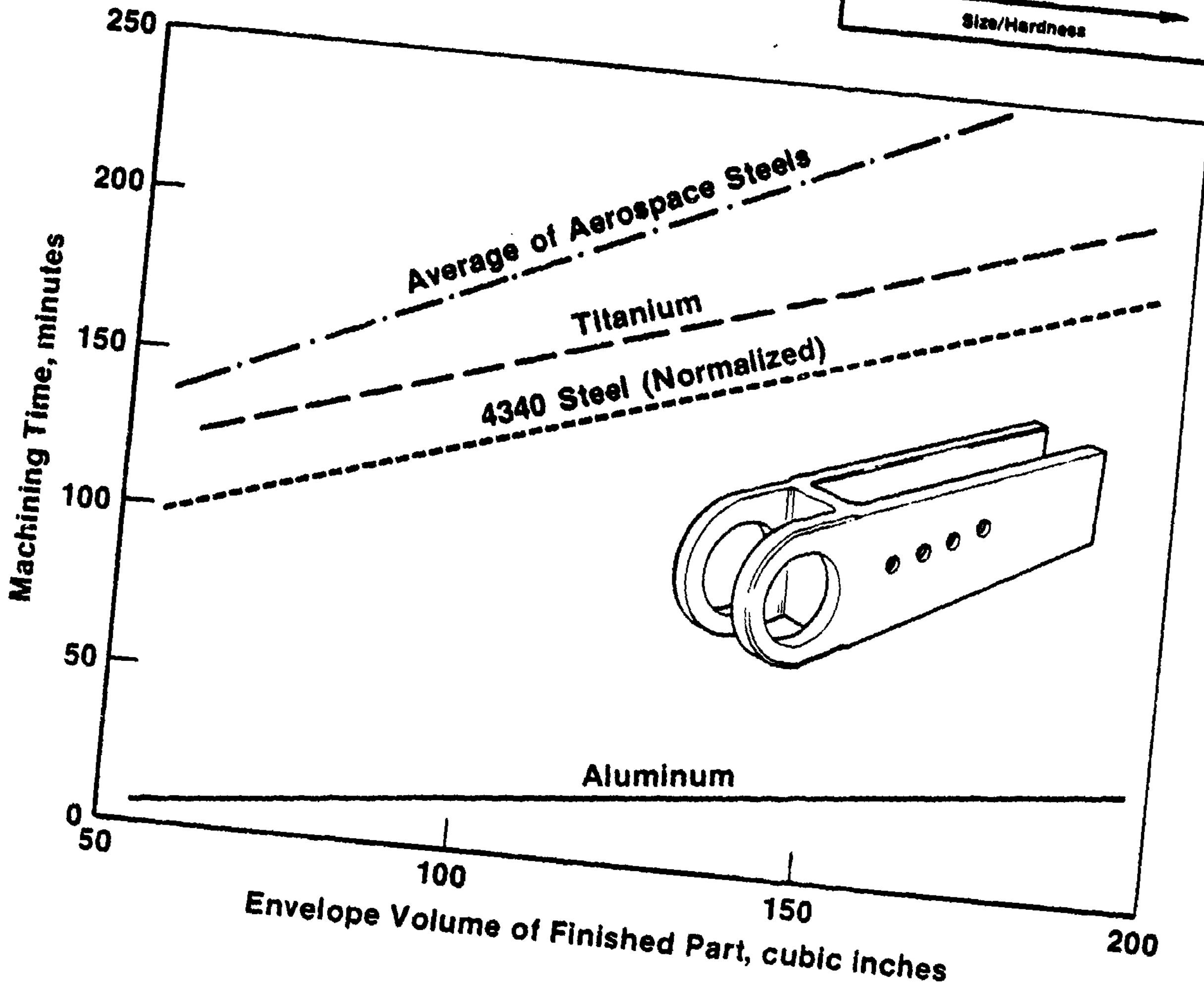
Part Type	Dimension, inches A	Dimension, inches B	Material
	10.0	0.250	Steel
			Titanium
			Aluminum
	12.5	0.375	Steel
			Titanium
			Aluminum
	15.0	0.500	Steel
			Titanium
			Aluminum



C: Average of Aerospace Steels
D: 4340 Steel (Normalized)

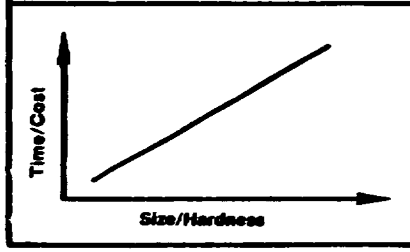
EFFECT OF SIZE AND MATERIAL ON MACHINING TIME OF FITTINGS

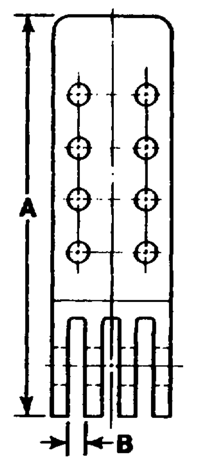
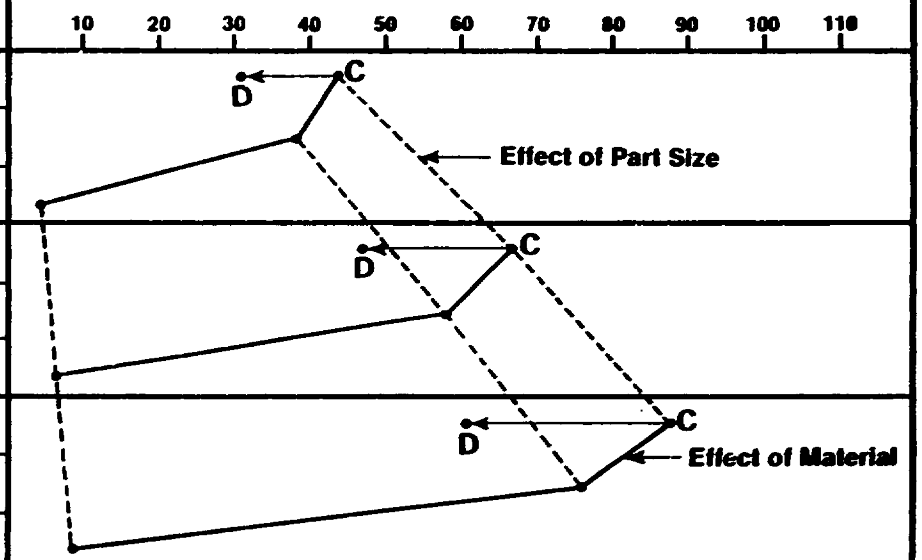




EFFECT OF SIZE AND MATERIAL ON MACHINING TIME OF FITTINGS

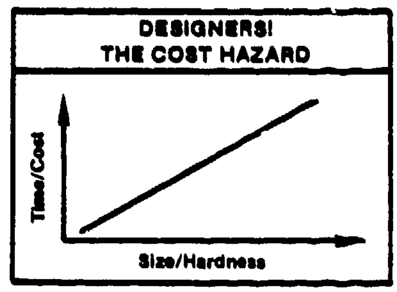
DESIGNERS! THE COST HAZARD

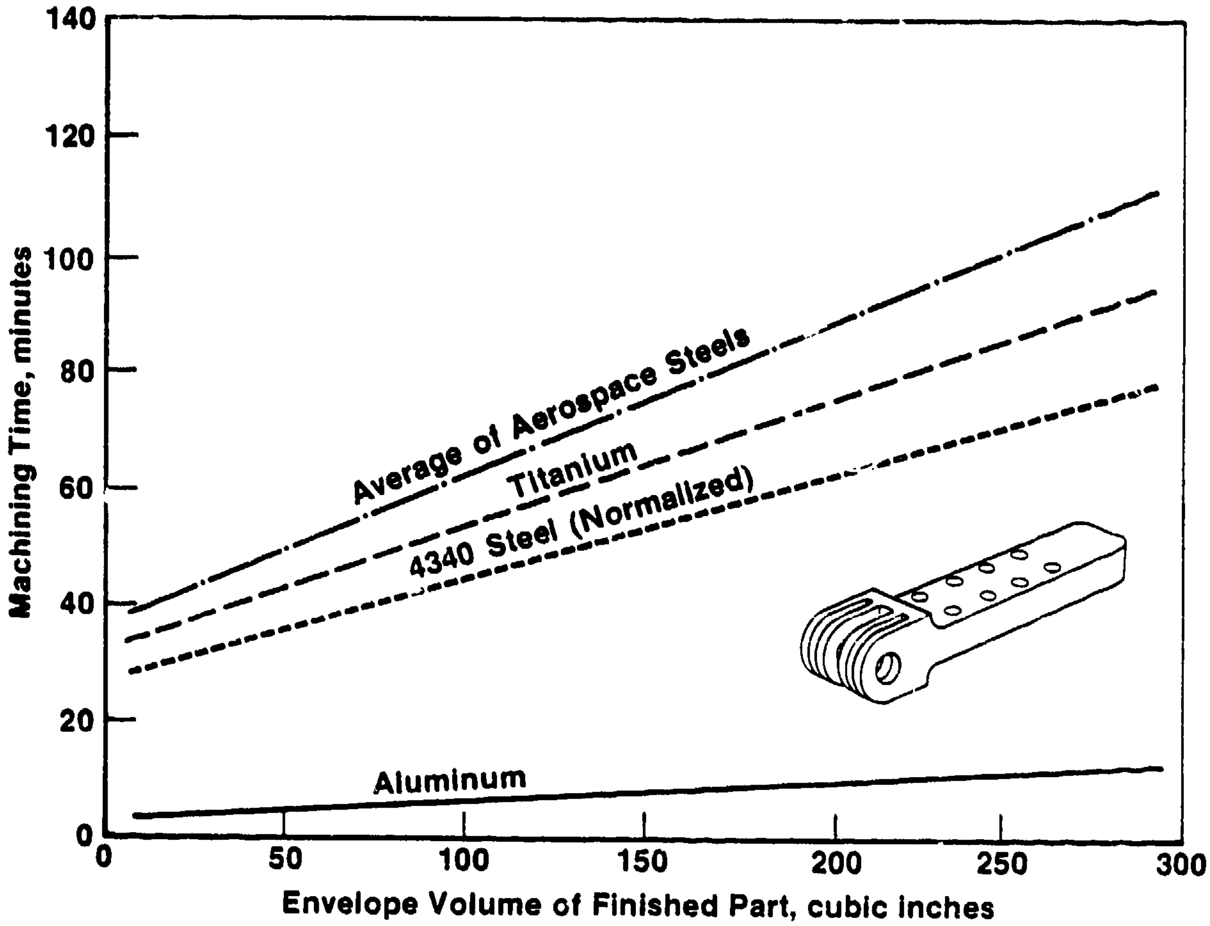


Part Type	Dimension, inches A	Dimension, inches B	Material	Machining Time, minutes
	10.0	0.250	Steel	
			Titanium	
			Aluminum	
	15.0	0.375	Steel	
			Titanium	
			Aluminum	
	20.0	0.500	Steel	
			Titanium	
			Aluminum	

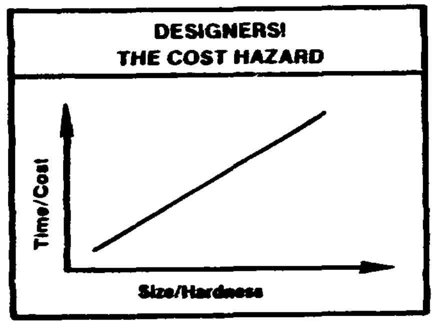
C: Average of Aerospace Steels
D: 4340 Steel (Normalized)

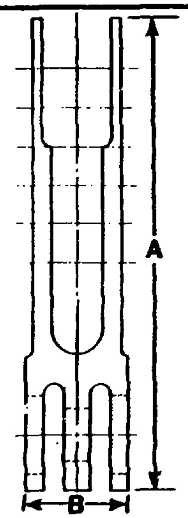
EFFECT OF SIZE AND MATERIAL ON MACHINING TIME OF FITTINGS

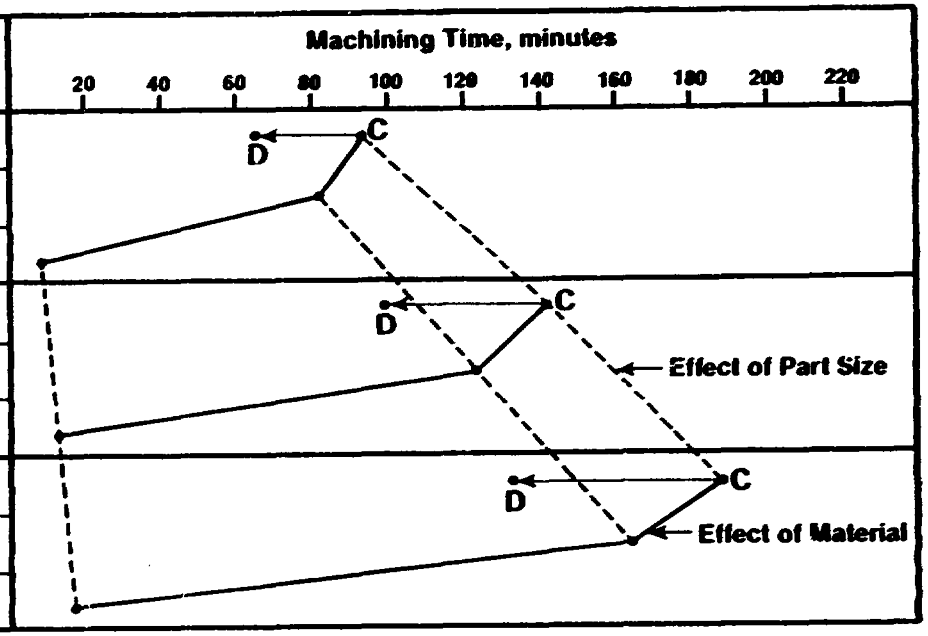




EFFECT OF SIZE AND MATERIAL ON MACHINING TIME OF FITTINGS



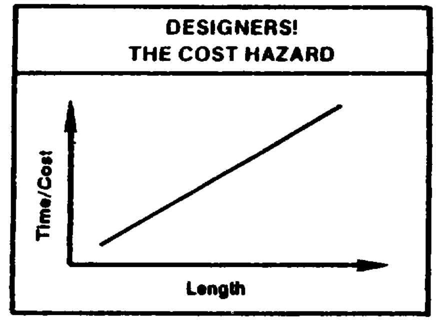
Part Type	Dimension, inches A	Dimension, inches B	Material
	10.0	2.0	Steel
			Titanium
			Aluminum
	14.5	3.0	Steel
			Titanium
			Alumin :n
	20.0	4.0	Steel
			Titanium
			Aluminum

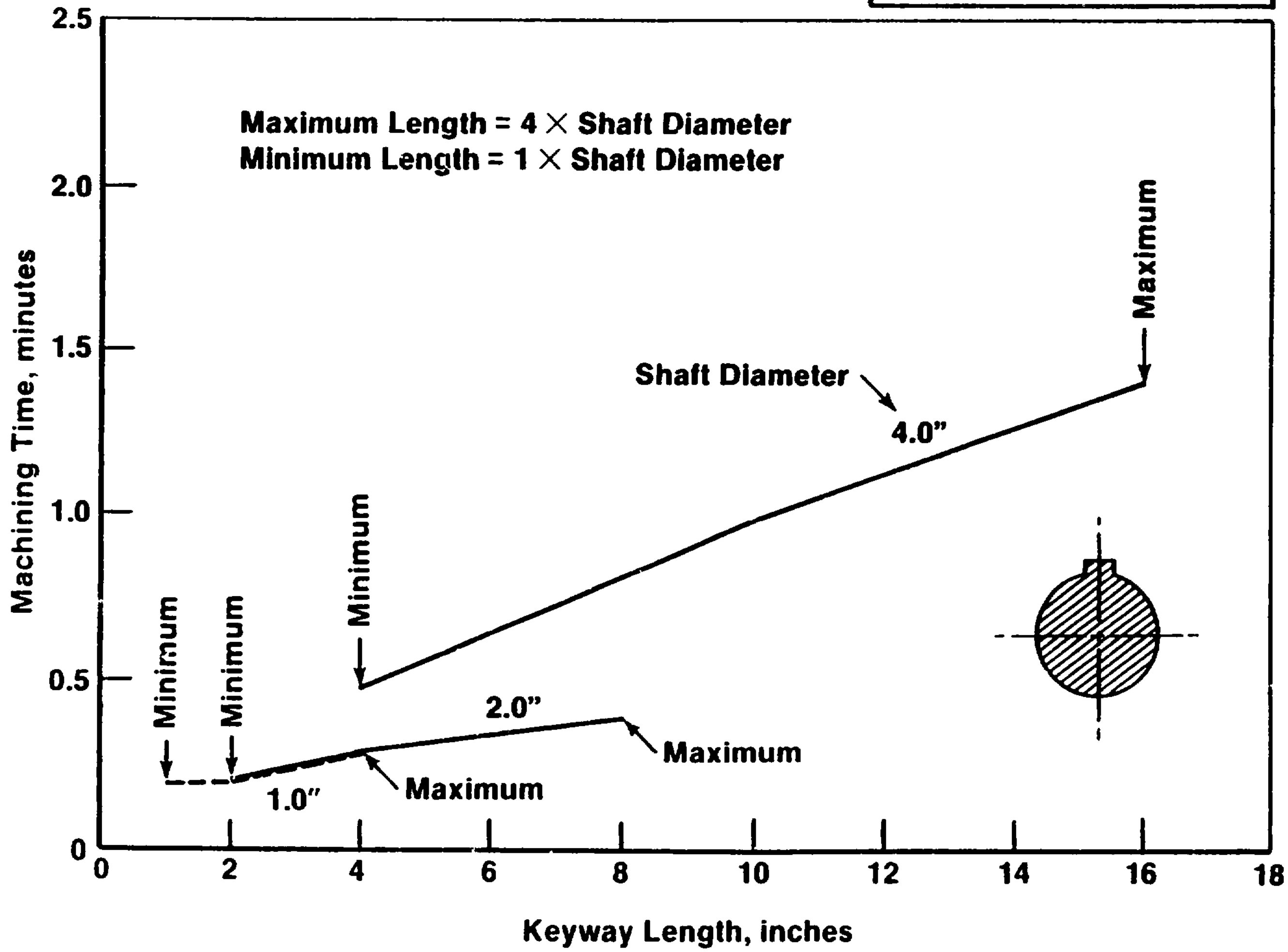


C: Average of Aerospace Steels
D: 4340 Steel (Normalized)

EFFECT OF LENGTH OF EXTERNAL KEYWAY (SQUARE TYPE) FOR:

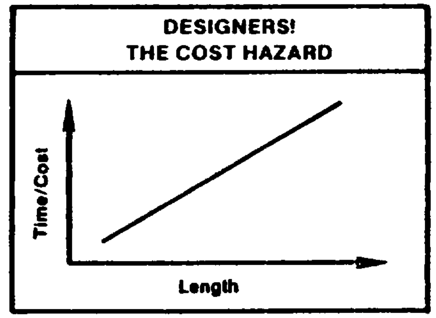
ALUMINUM

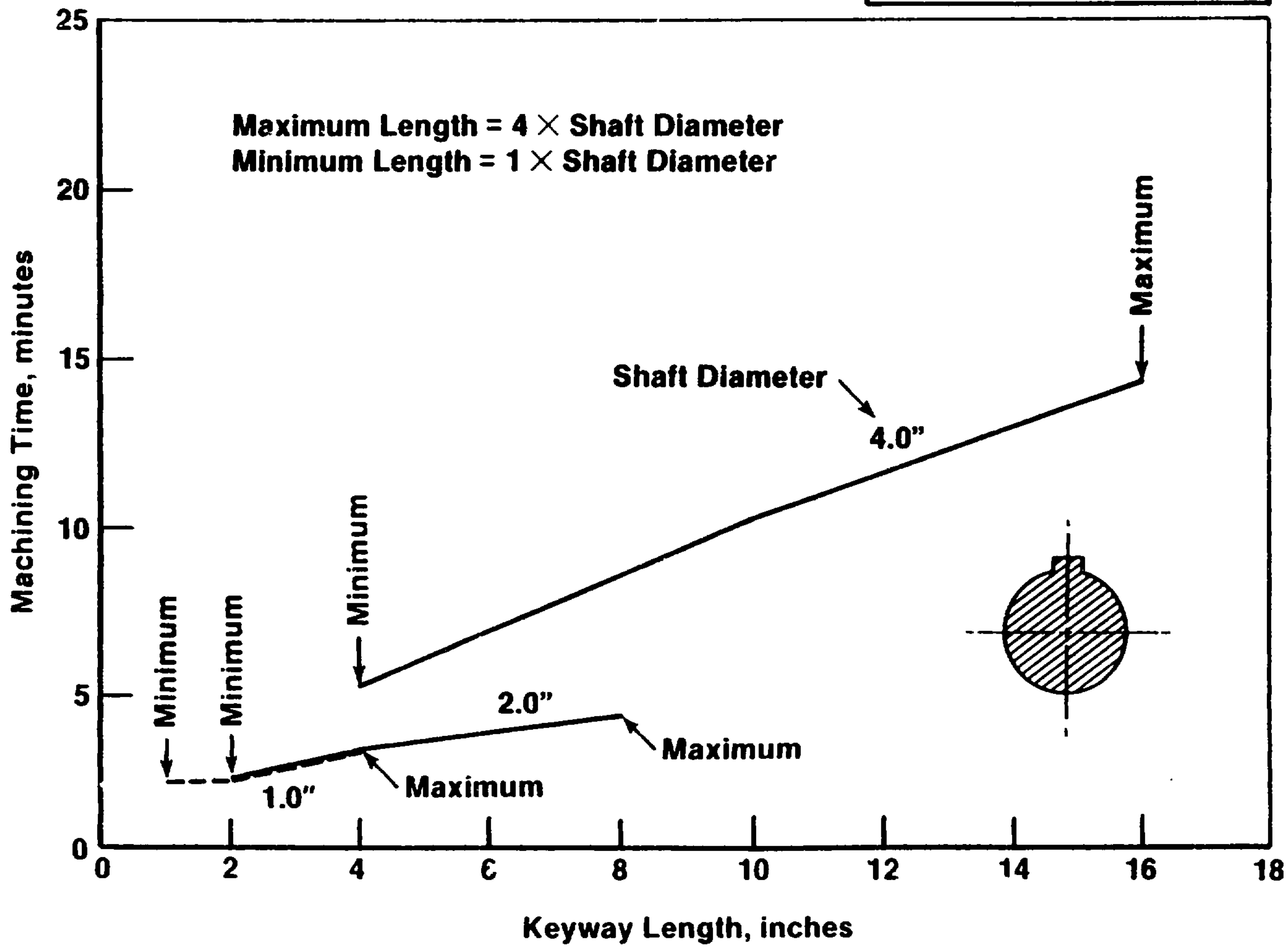




EFFECT OF LENGTH OF EXTERNAL KEYWAY (SQUARE TYPE) FOR:

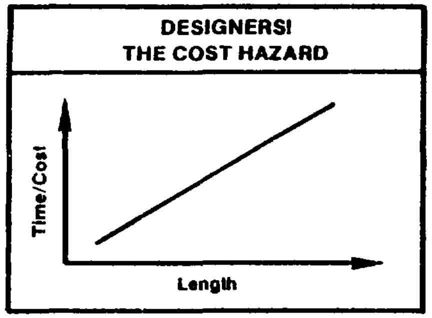
TITANIUM

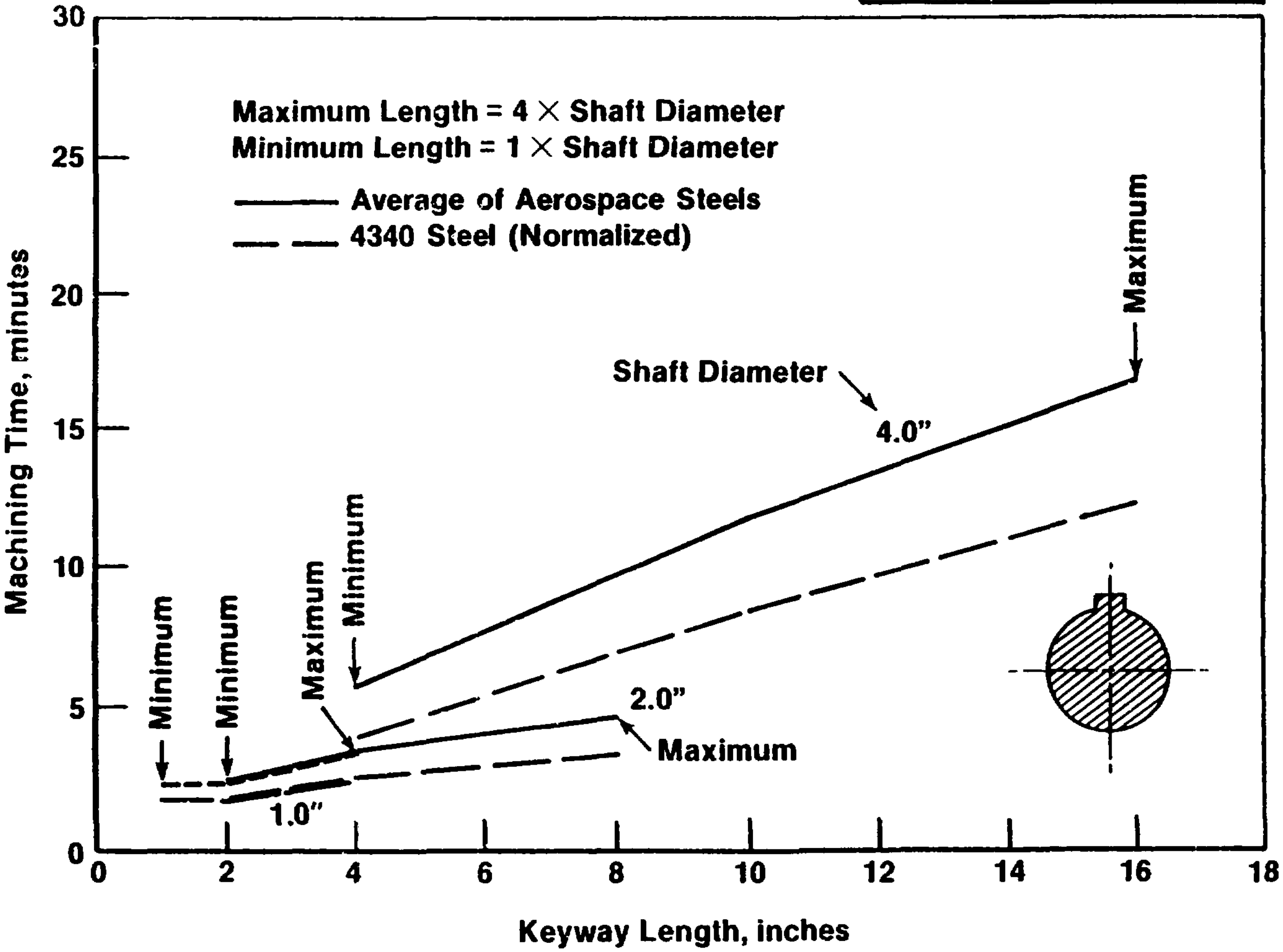




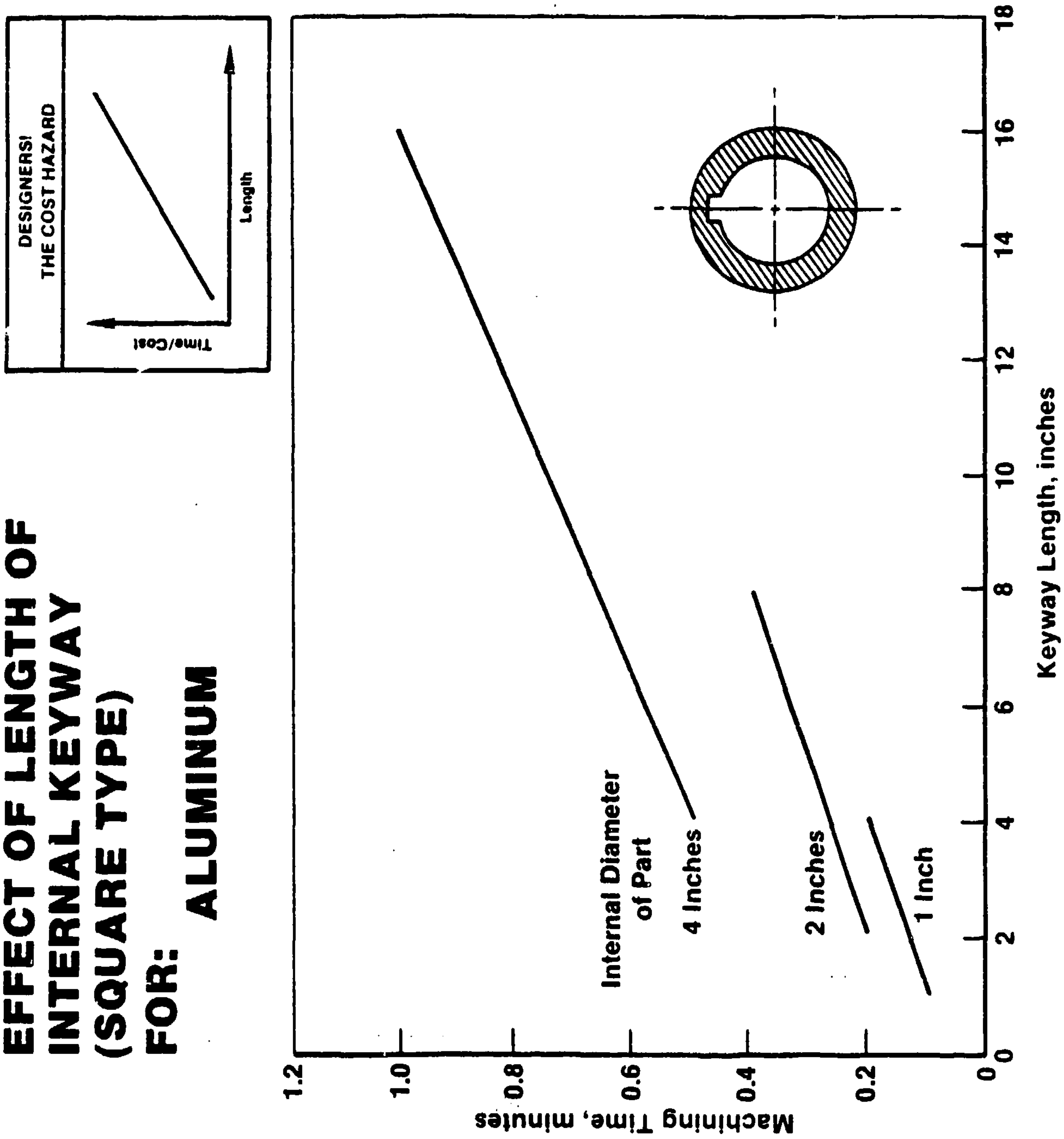
EFFECT OF LENGTH OF EXTERNAL KEYWAY (SQUARE TYPE) FOR:

HIGH STRENGTH STEELS





EFFECT OF LENGTH OF INTERNAL KEYWAY (SQUARE TYPE) FOR: ALUMINUM



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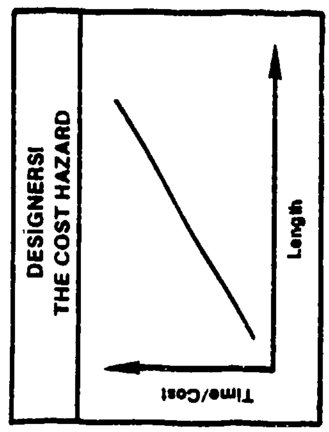
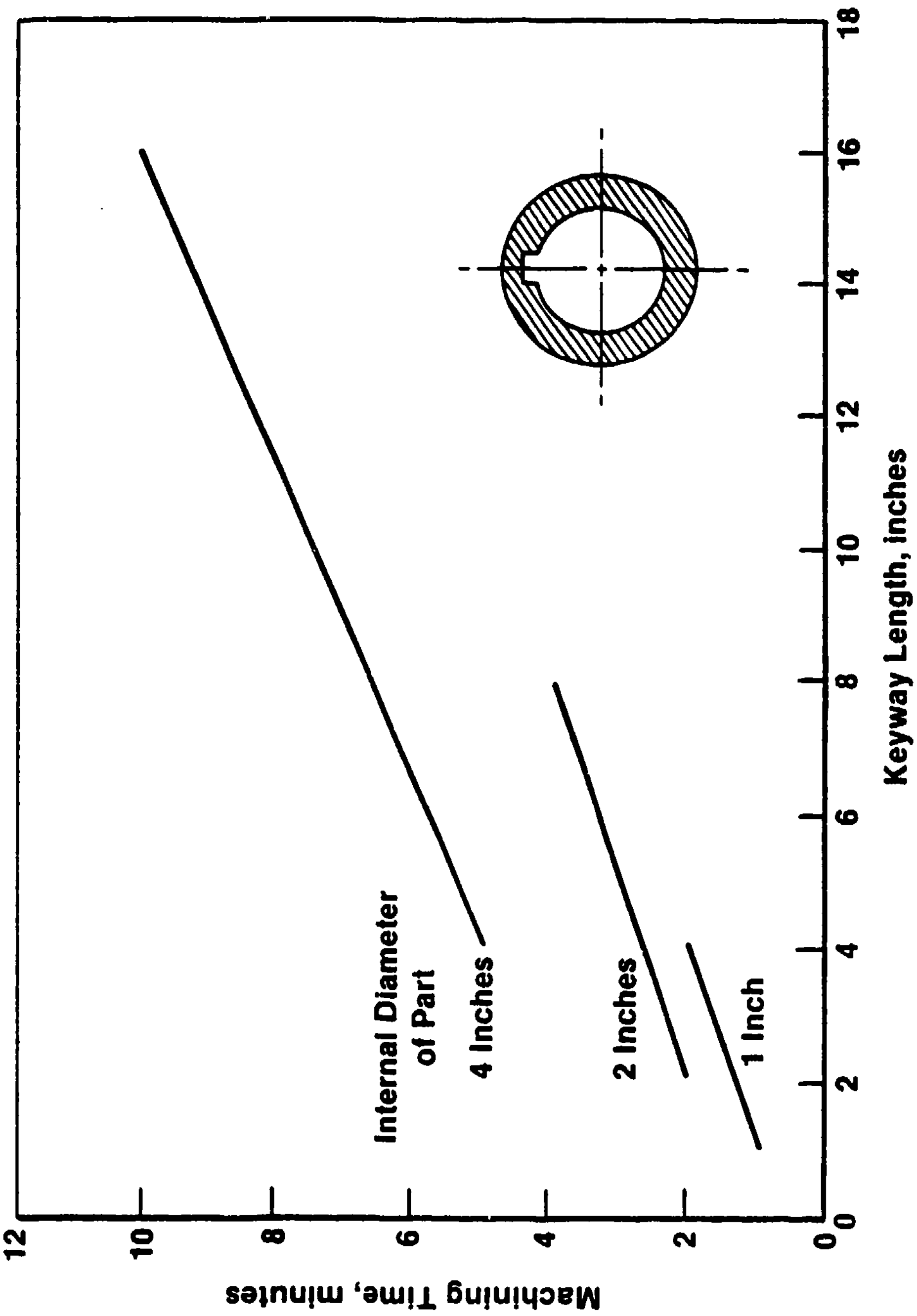
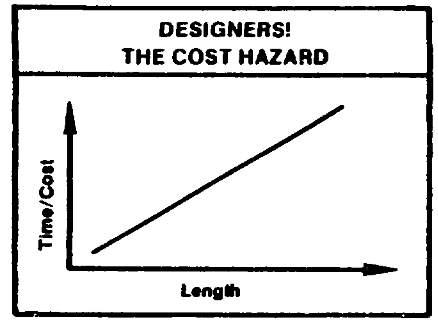
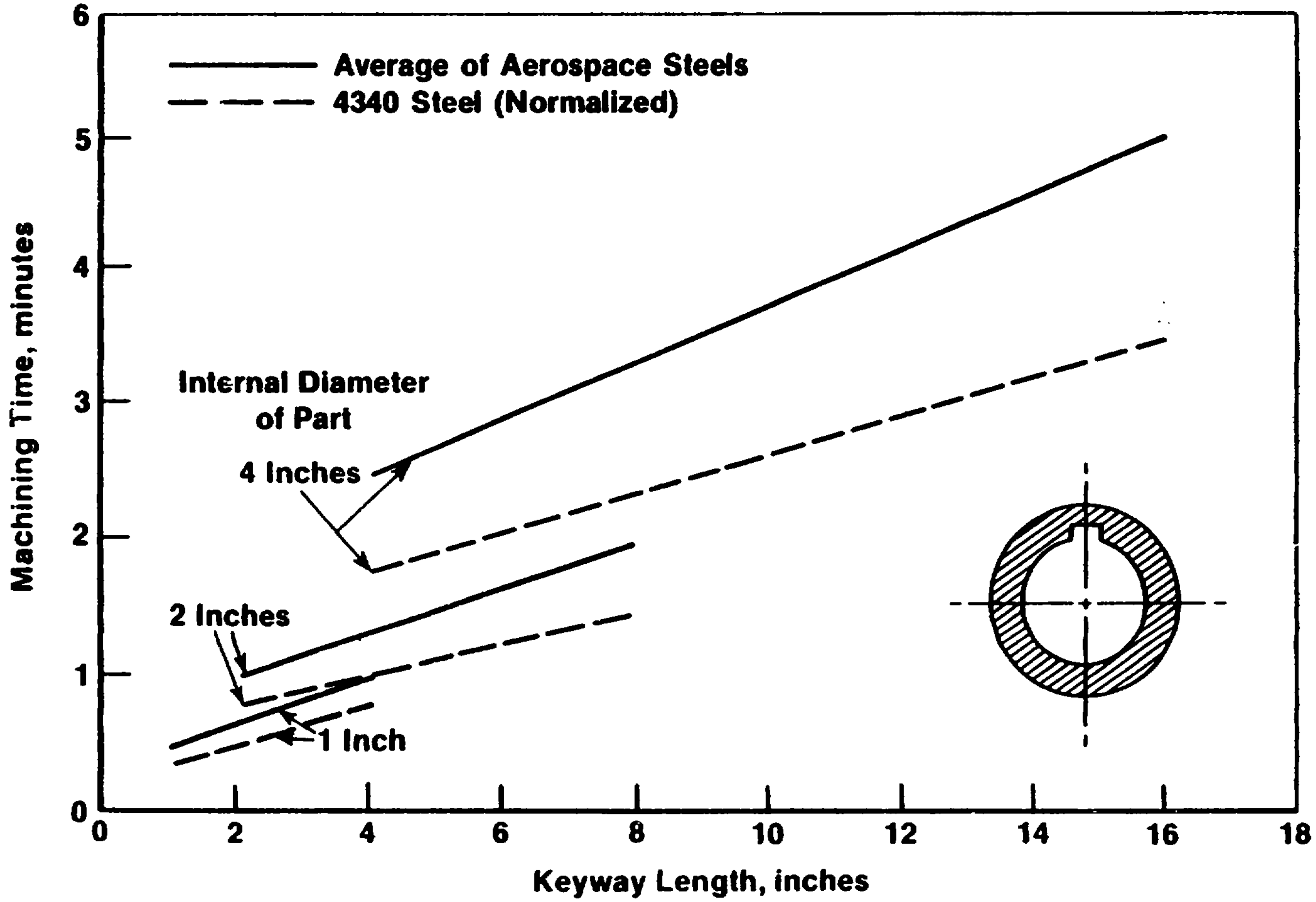
EFFECT OF LENGTH OF INTERNAL KEYWAY (SQUARE TYPE) FOR: TITANIUM





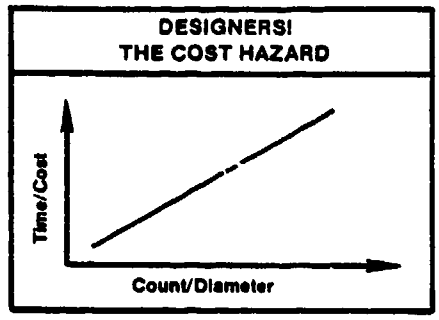
EFFECT OF LENGTH OF INTERNAL KEYWAY (SQUARE TYPE) FOR: HIGH STRENGTH STEELS

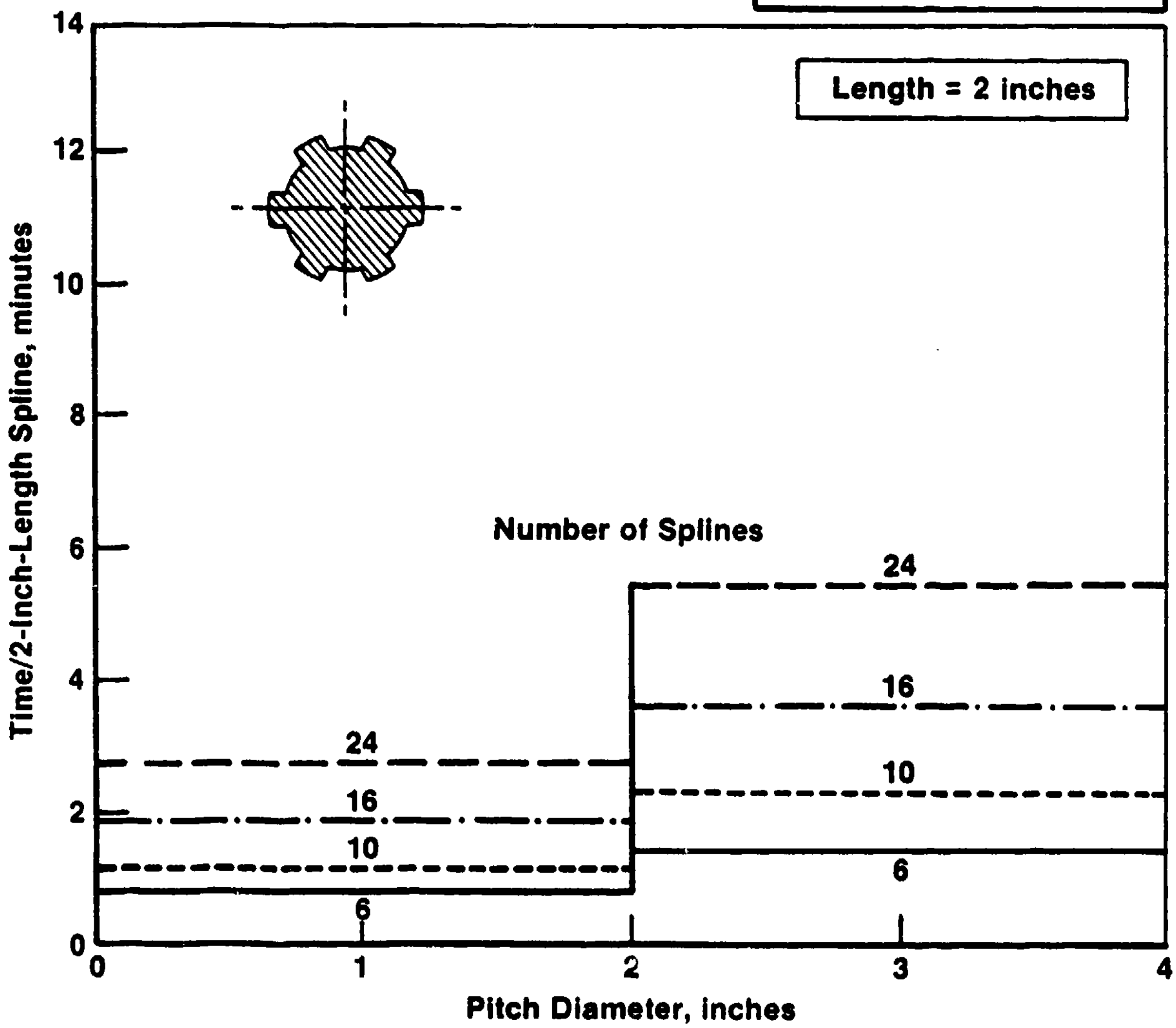




EFFECT OF NUMBER OF EXTERNAL SPLINES AND PART DIAMETER FOR:

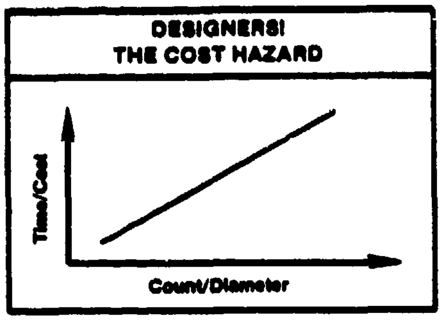
ALUMINUM

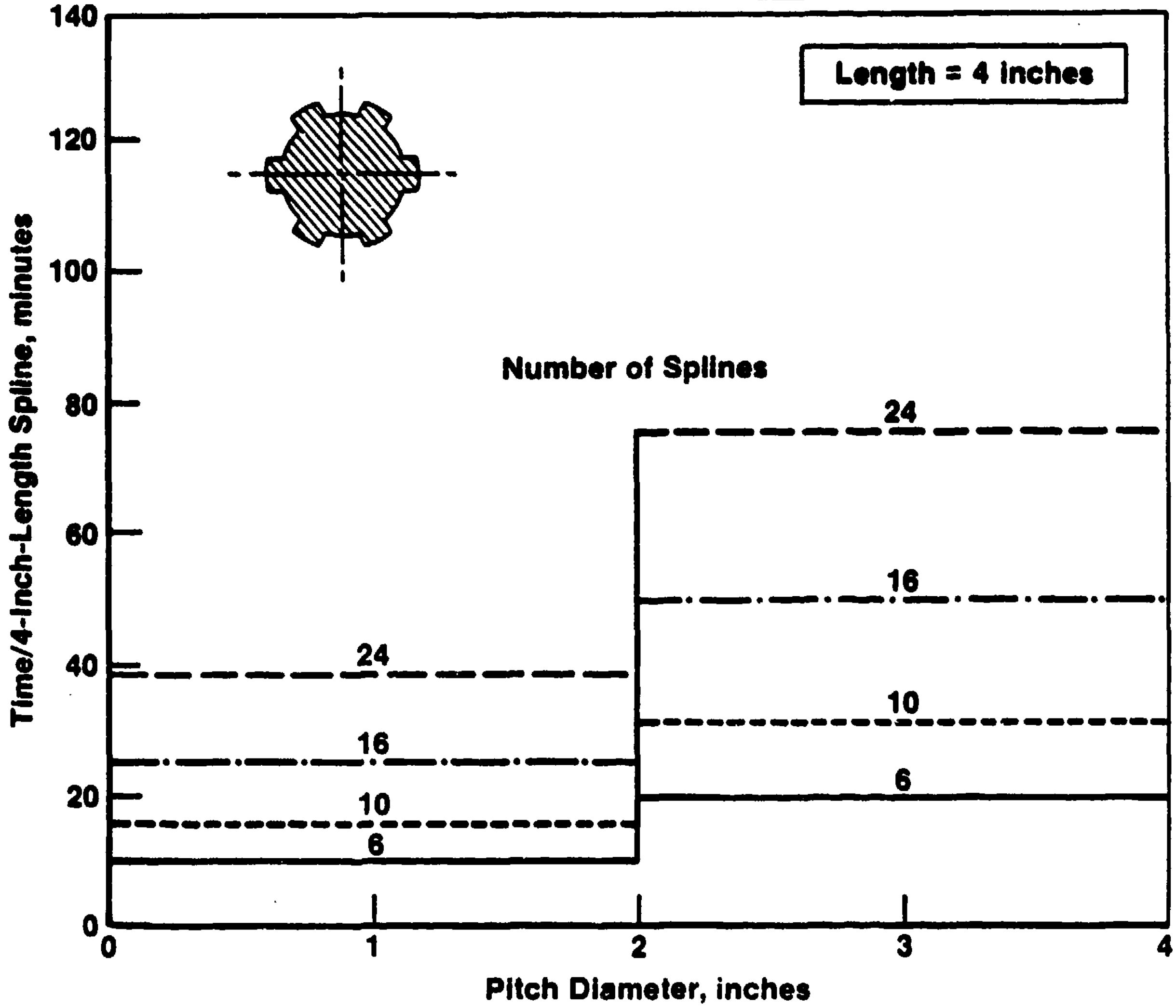




EFFECT OF NUMBER OF EXTERNAL SPLINES AND PART DIAMETER FOR:

ALUMINUM

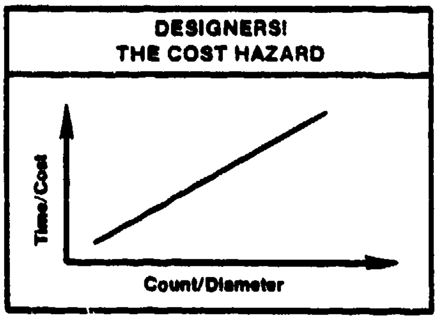


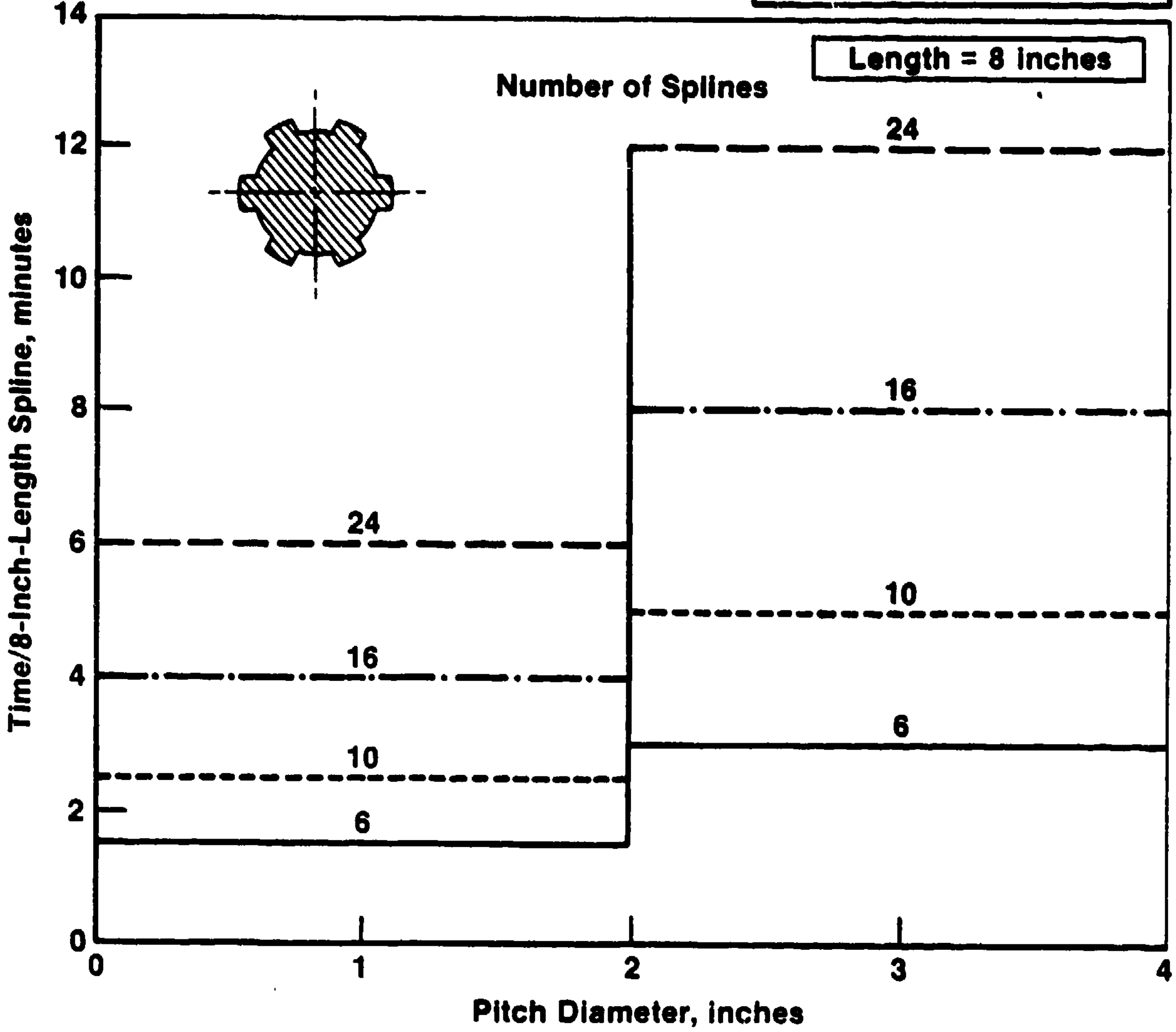


CED-M/C-53

EFFECT OF NUMBER OF EXTERNAL SPLINES AND PART DIAMETER FOR:

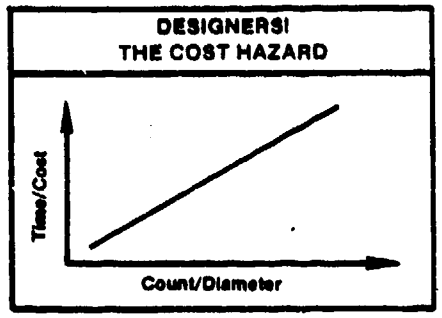
ALUMINUM

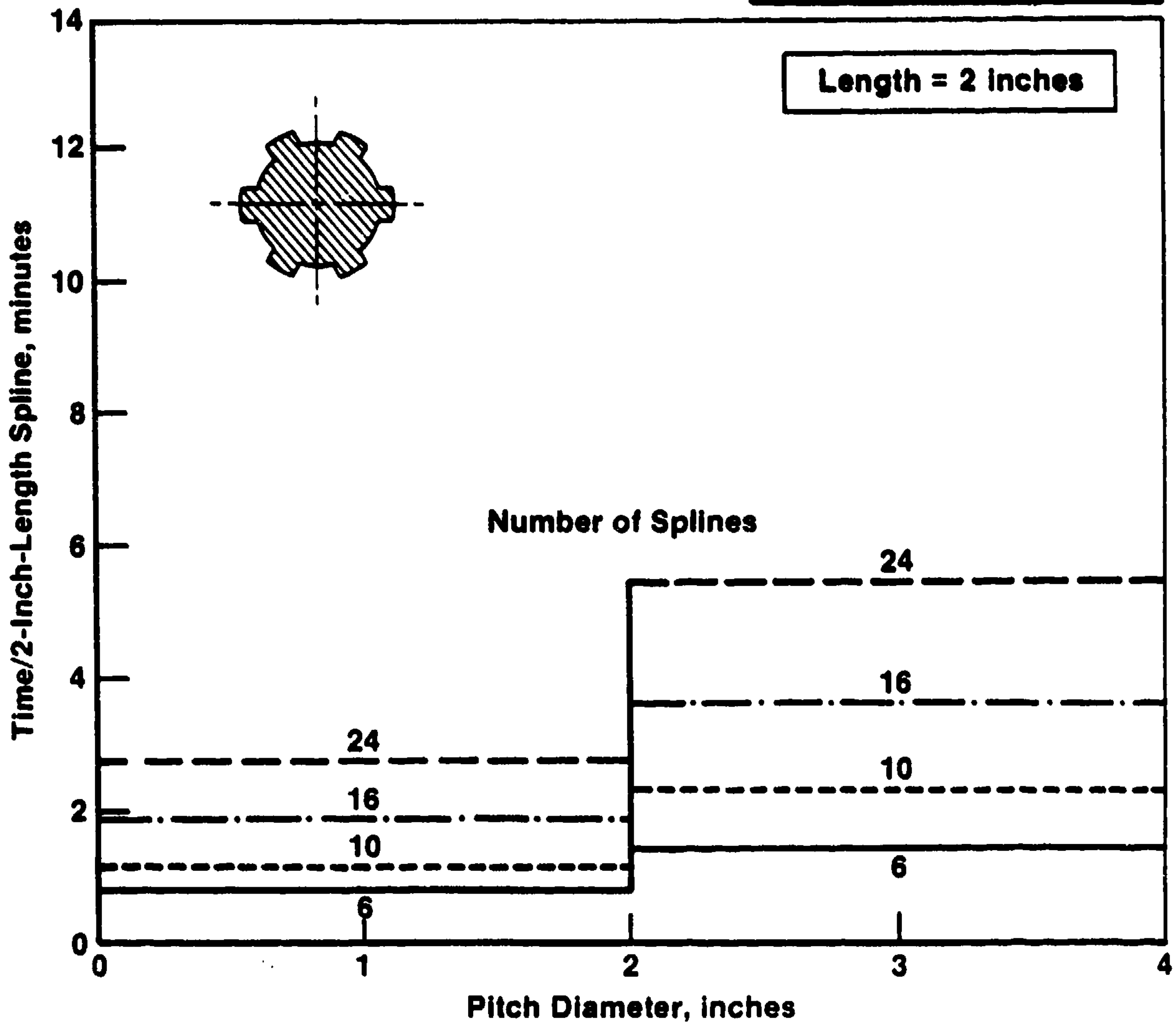




EFFECT OF NUMBER OF EXTERNAL SPLINES AND PART DIAMETER FOR:

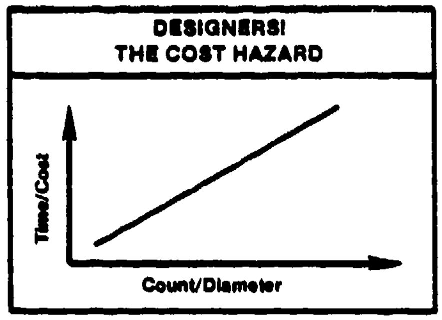
TITANIUM

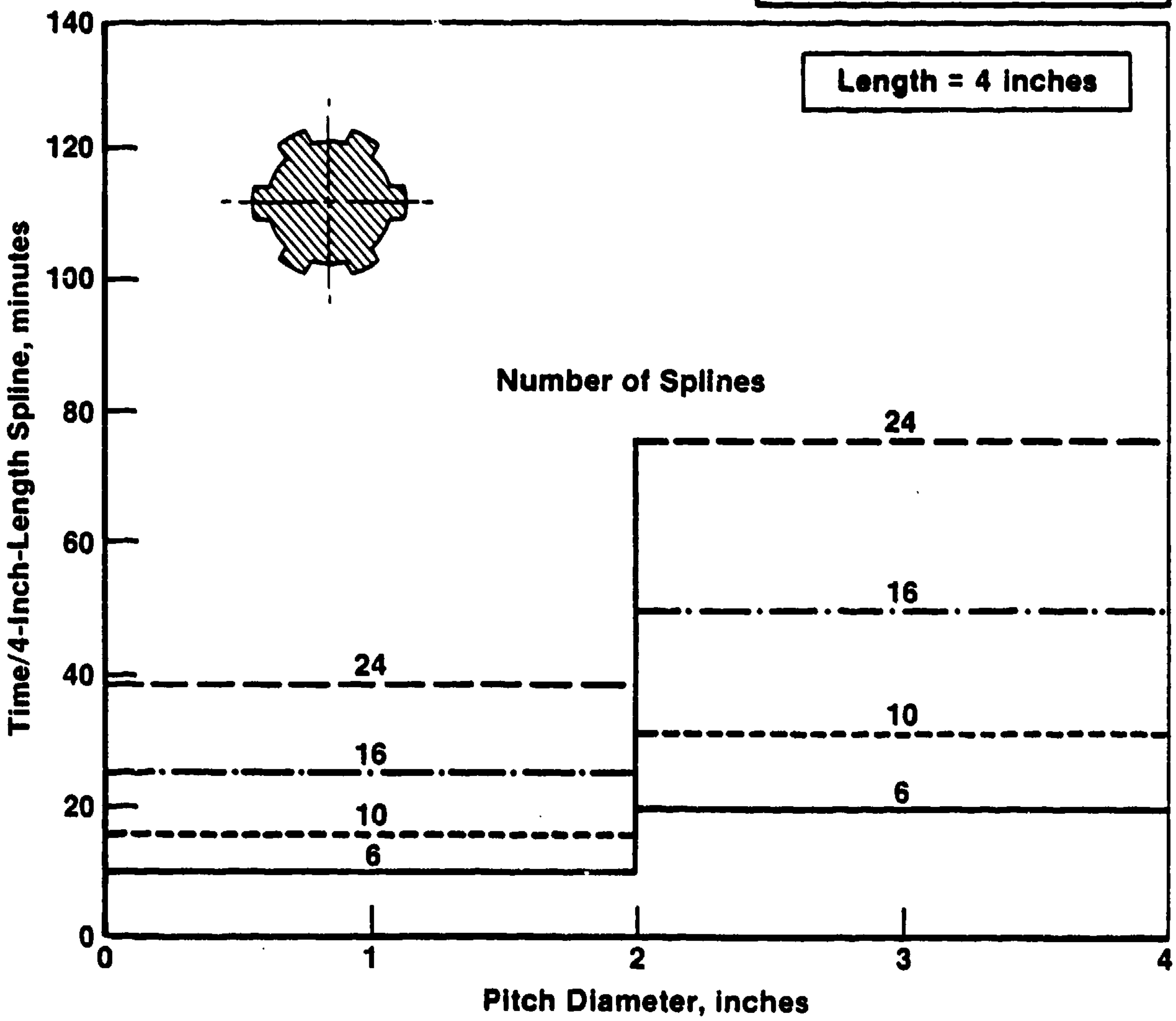




EFFECT OF NUMBER OF EXTERNAL SPLINES AND PART DIAMETER FOR:

TITANIUM

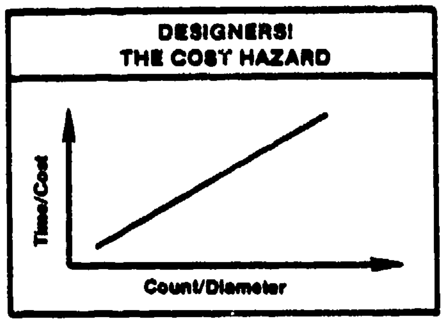


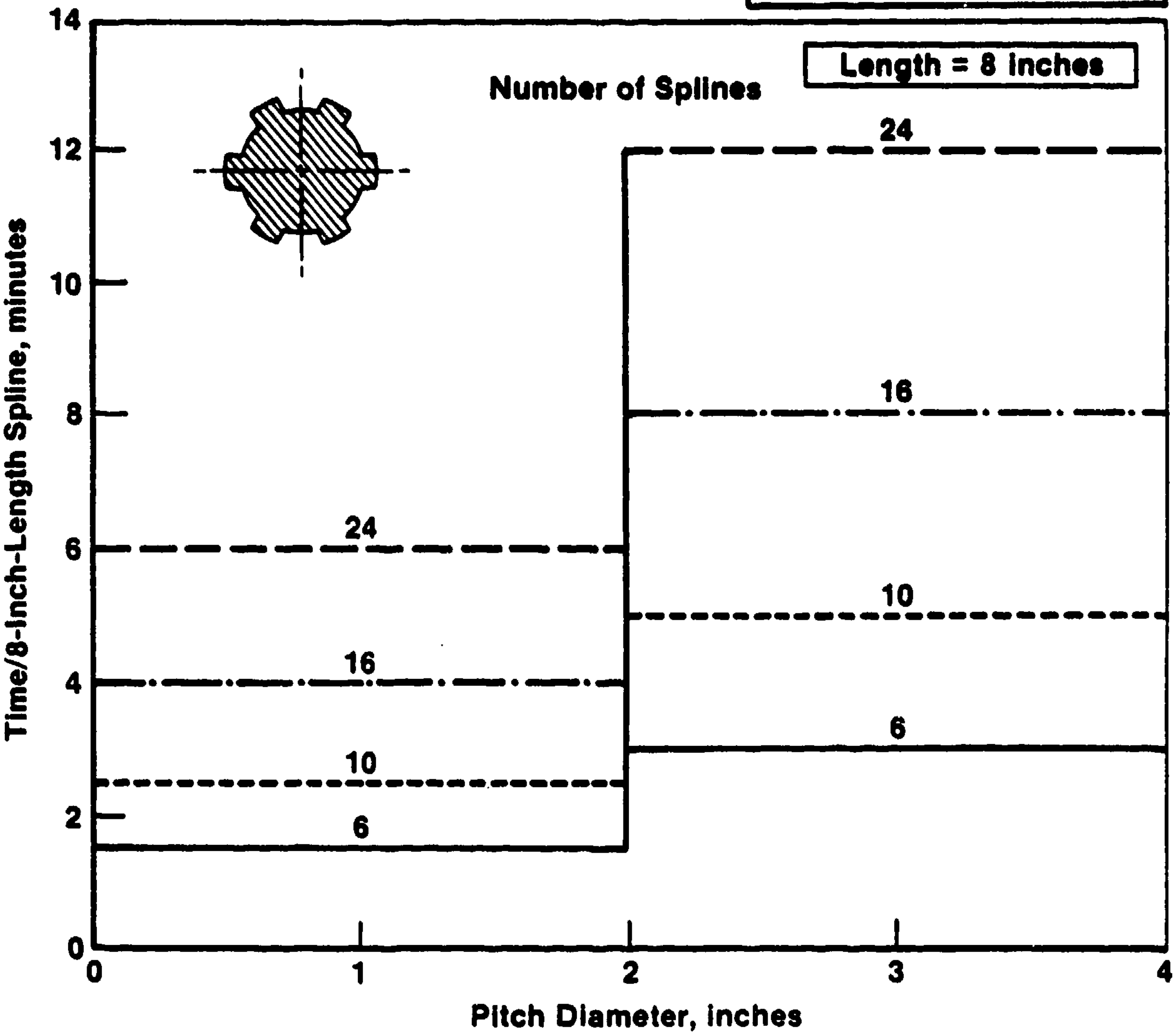


CED-M/C-56

EFFECT OF NUMBER OF EXTERNAL SPLINES AND PART DIAMETER FOR:

TITANIUM





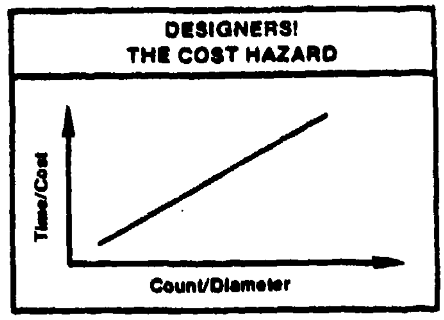
CED-M/C-57

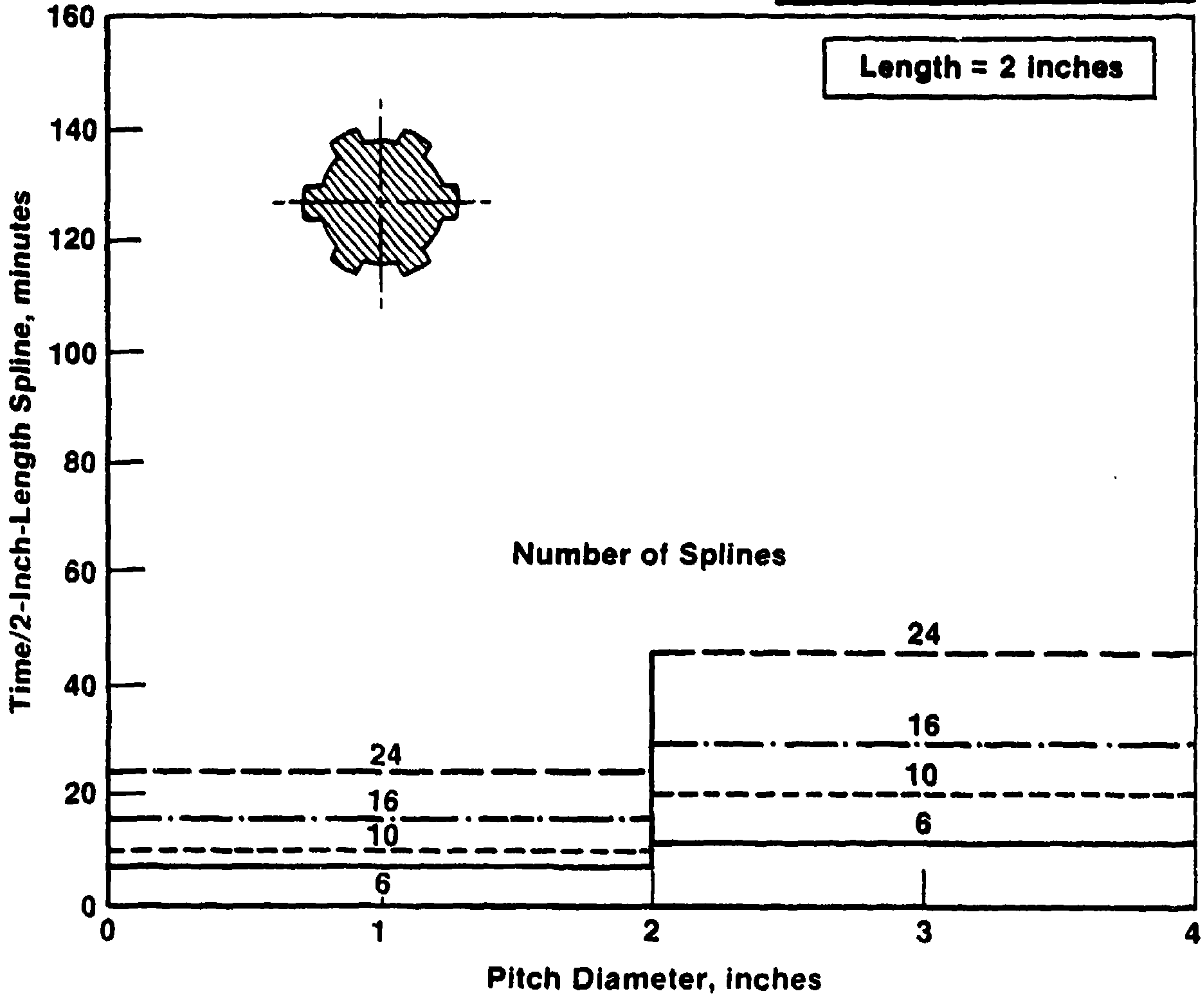
FTR450261000
6 Mar 1985

EFFECT OF NUMBER OF EXTERNAL SPLINES AND PART DIAMETER FOR:

HIGH STRENGTH STEELS

4340 Steel (Normalized)



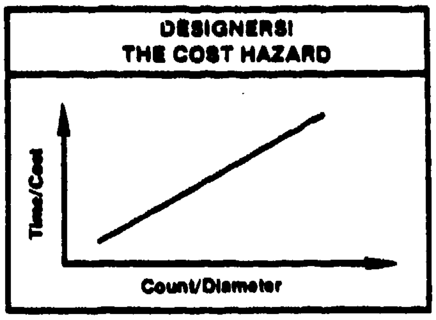


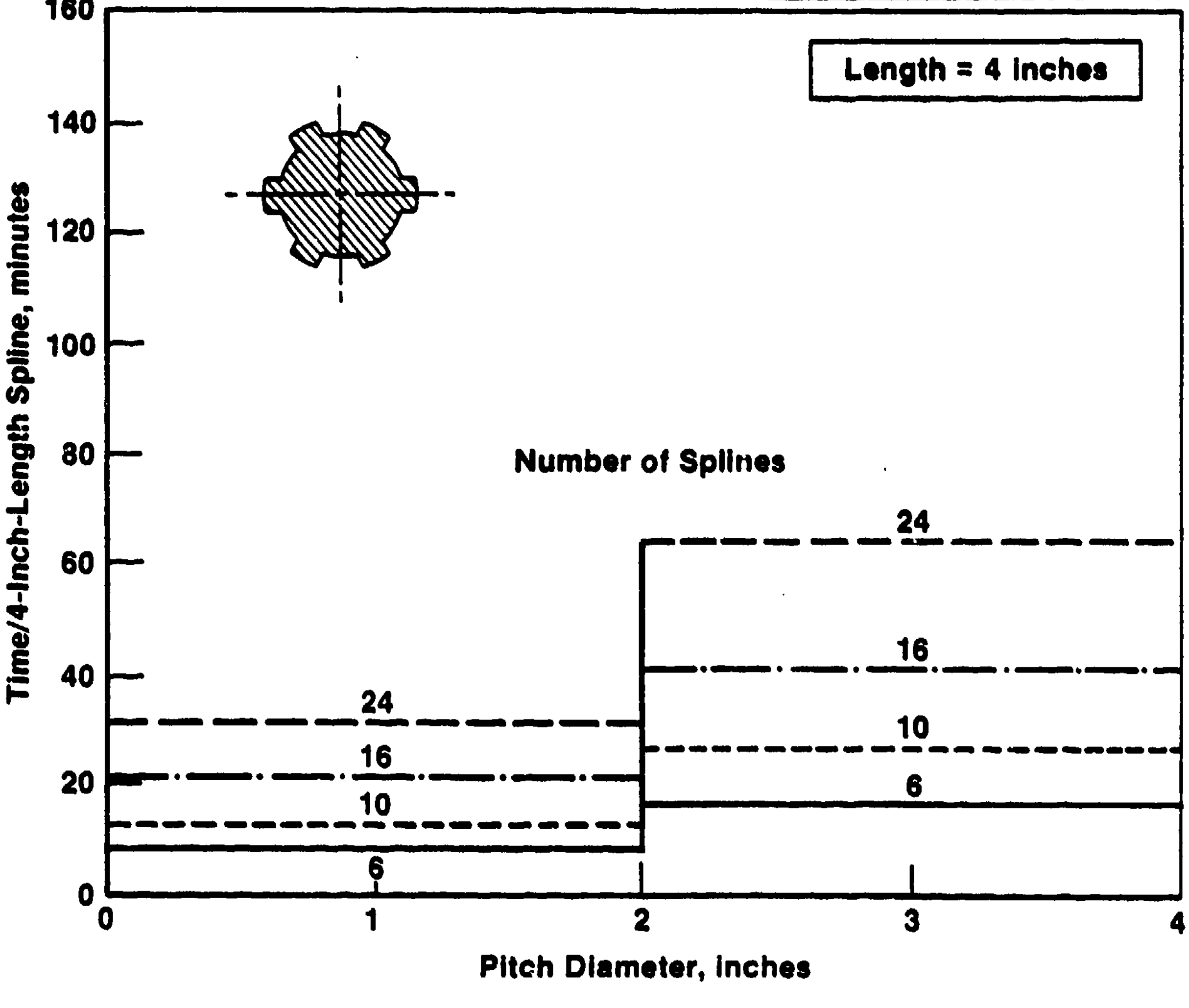
CED-M/C-58

EFFECT OF NUMBER OF EXTERNAL SPLINES AND PART DIAMETER FOR:

HIGH STRENGTH STEELS

4340 Steel (Normalized)

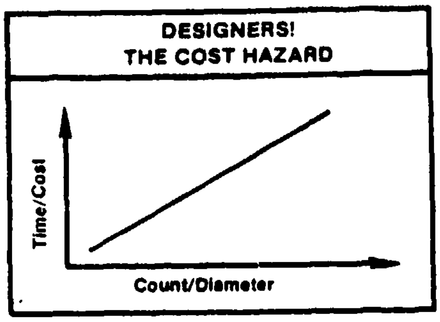


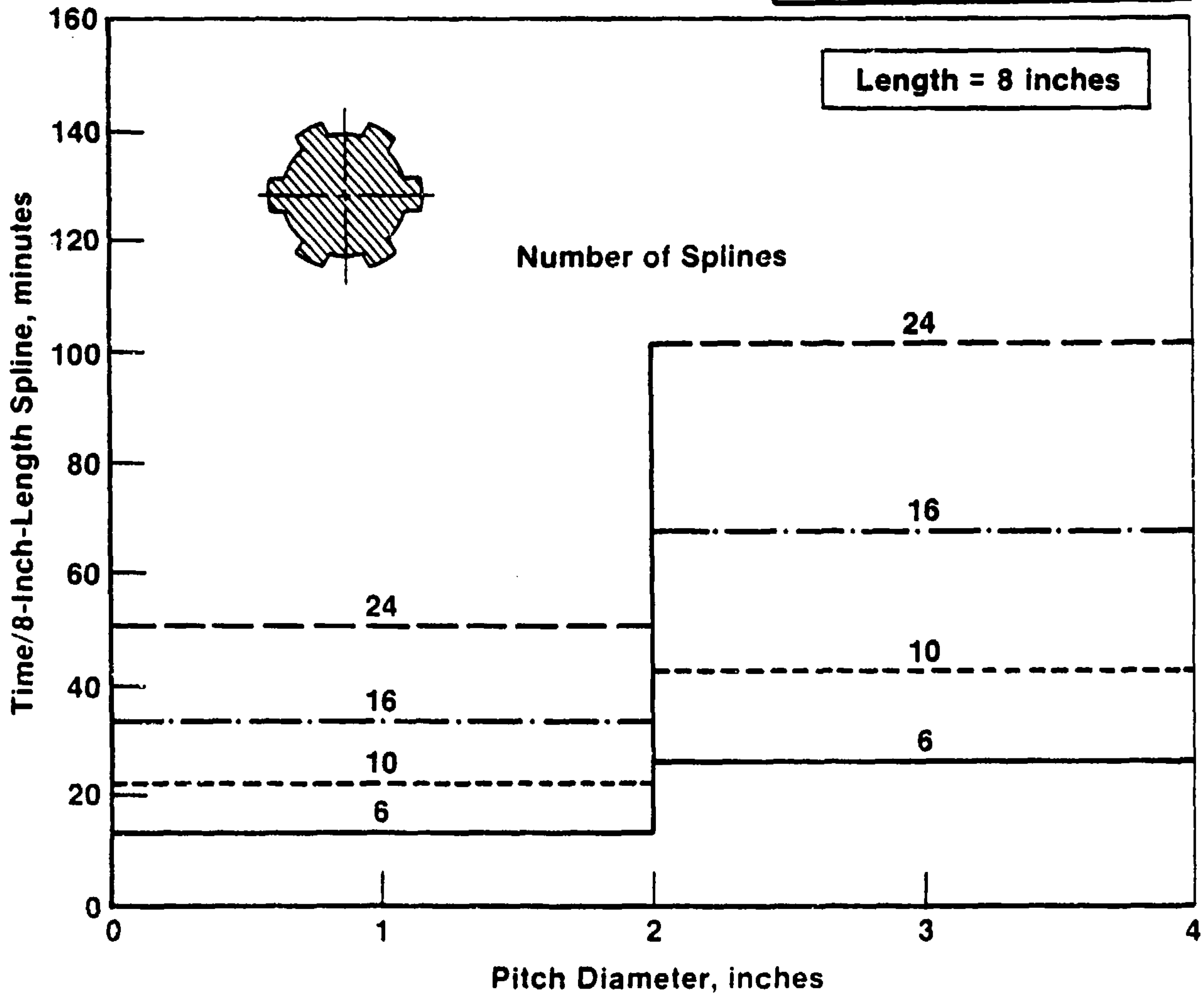


EFFECT OF NUMBER OF EXTERNAL SPLINES AND PART DIAMETER FOR:

HIGH STRENGTH STEELS

4340 Steel (Normalized)

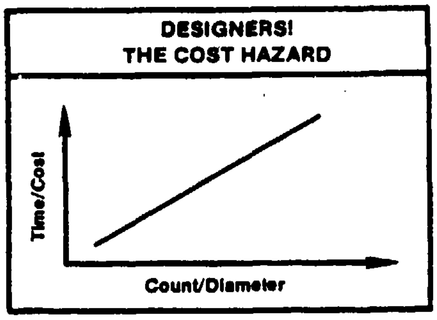


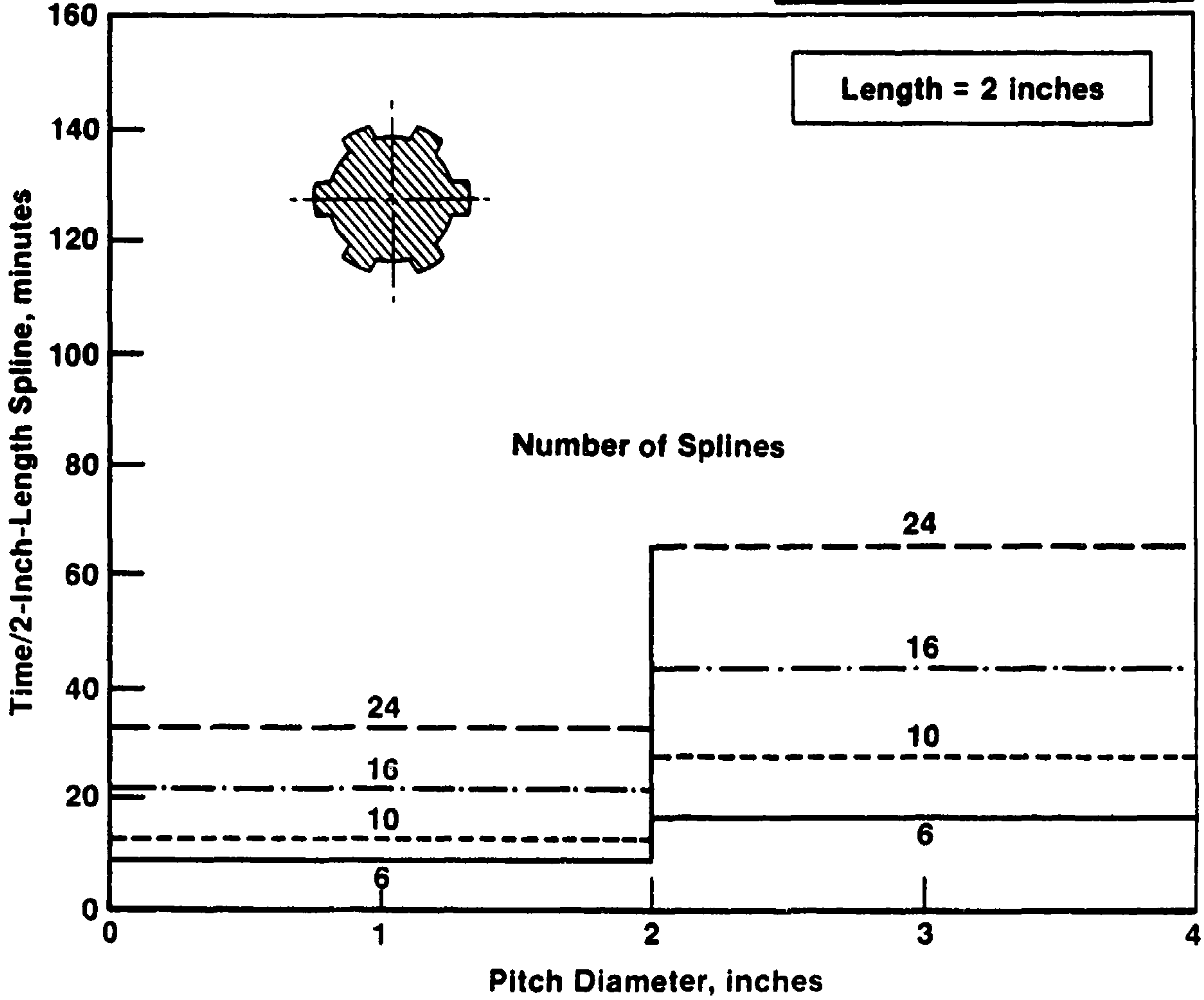


EFFECT OF NUMBER OF EXTERNAL SPLINES AND PART DIAMETER FOR:

HIGH STRENGTH STEELS

Average of Aerospace Steels

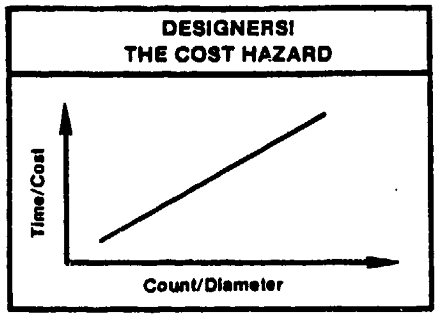


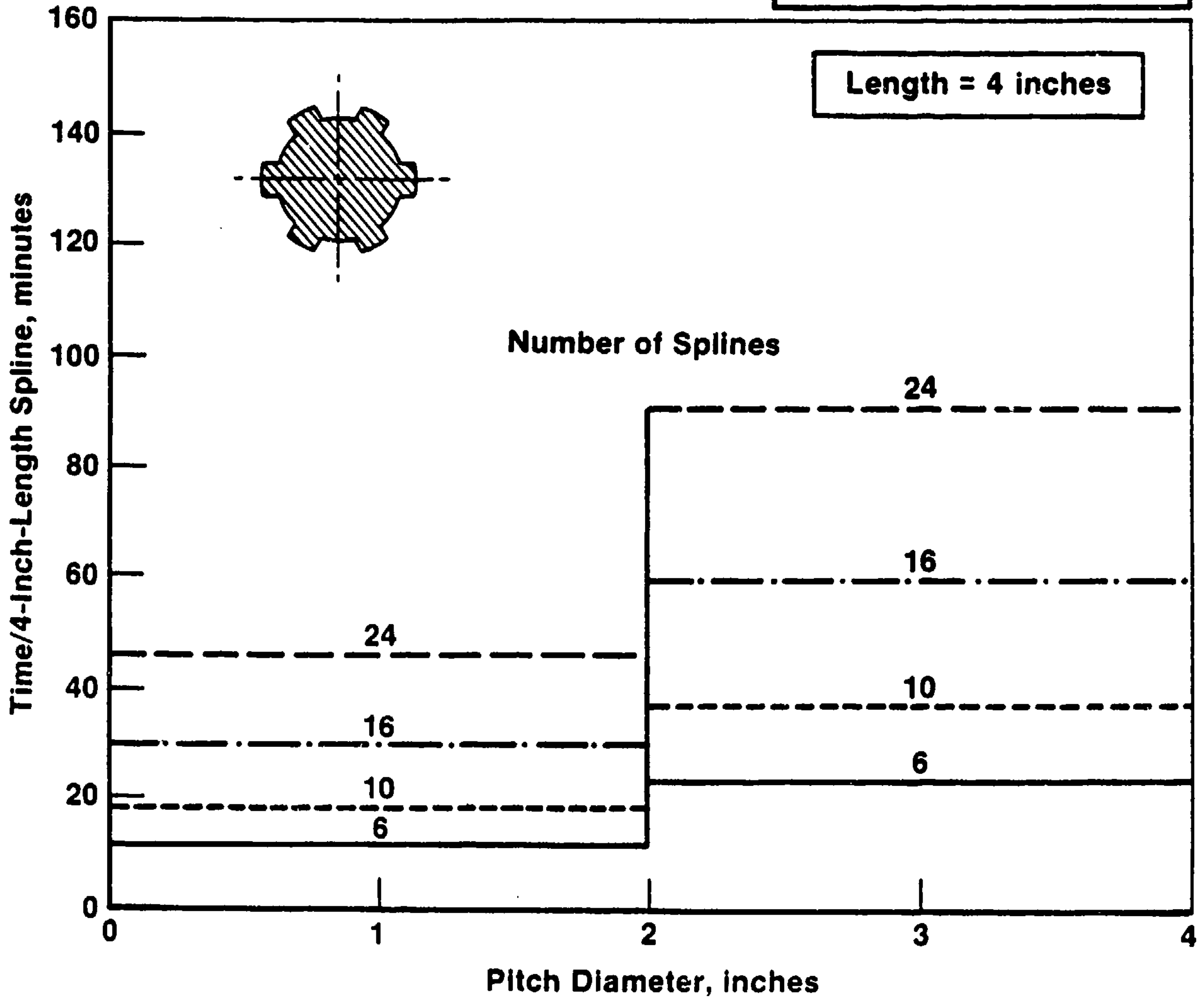


EFFECT OF NUMBER OF EXTERNAL SPLINES AND PART DIAMETER FOR:

HIGH STRENGTH STEELS

Average of Aerospace Steels





CED-M/C-62

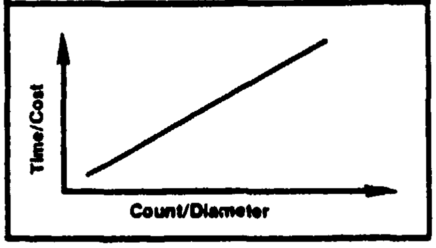
FTR450261000
6 Mar 1985

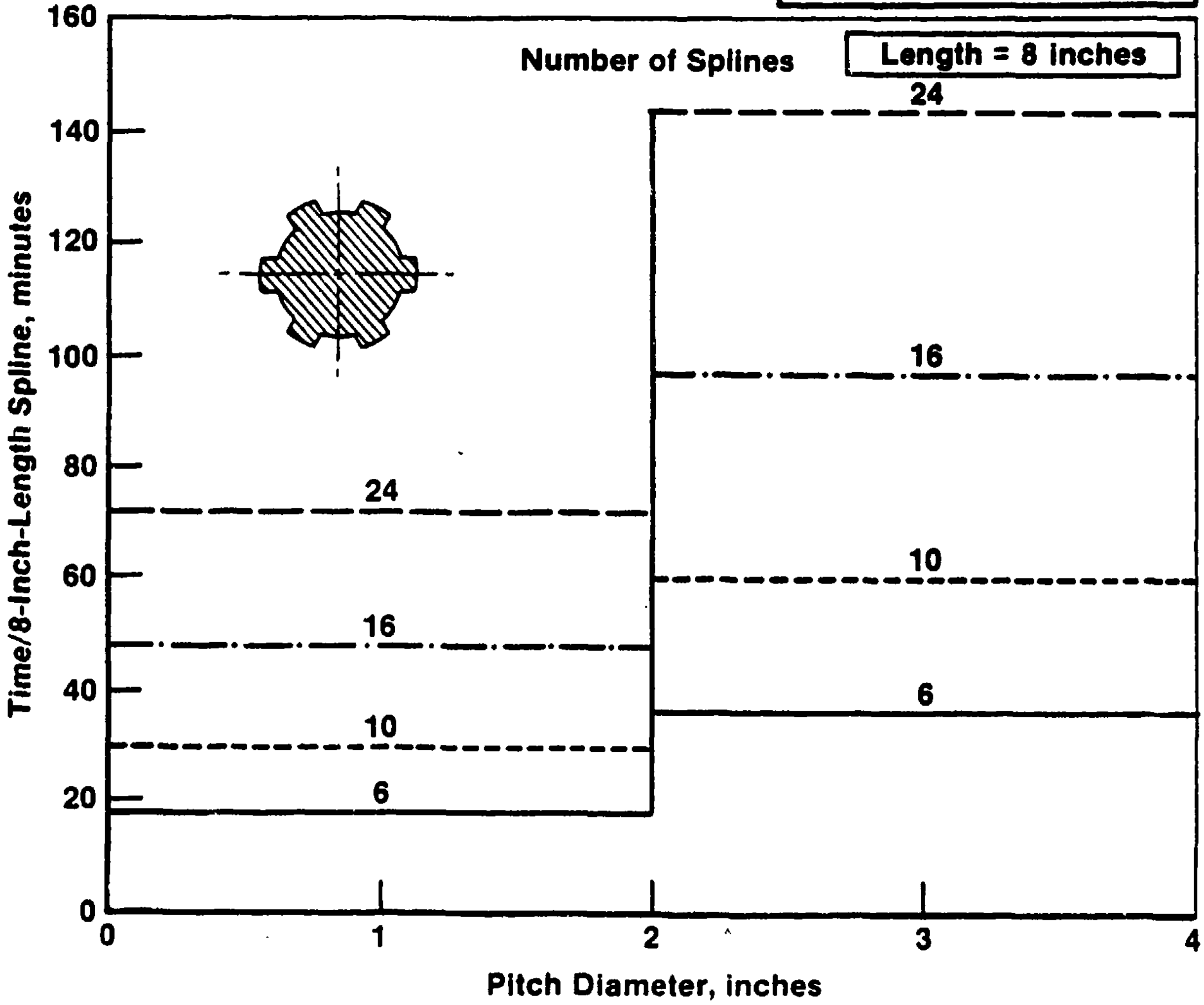
EFFECT OF NUMBER OF EXTERNAL SPLINES AND PART DIAMETER FOR:

HIGH STRENGTH STEELS

Average of Aerospace Steels

DESIGNERS!
THE COST HAZARD

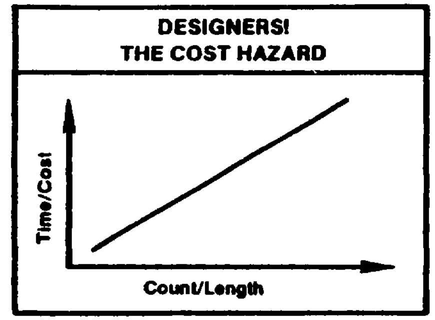


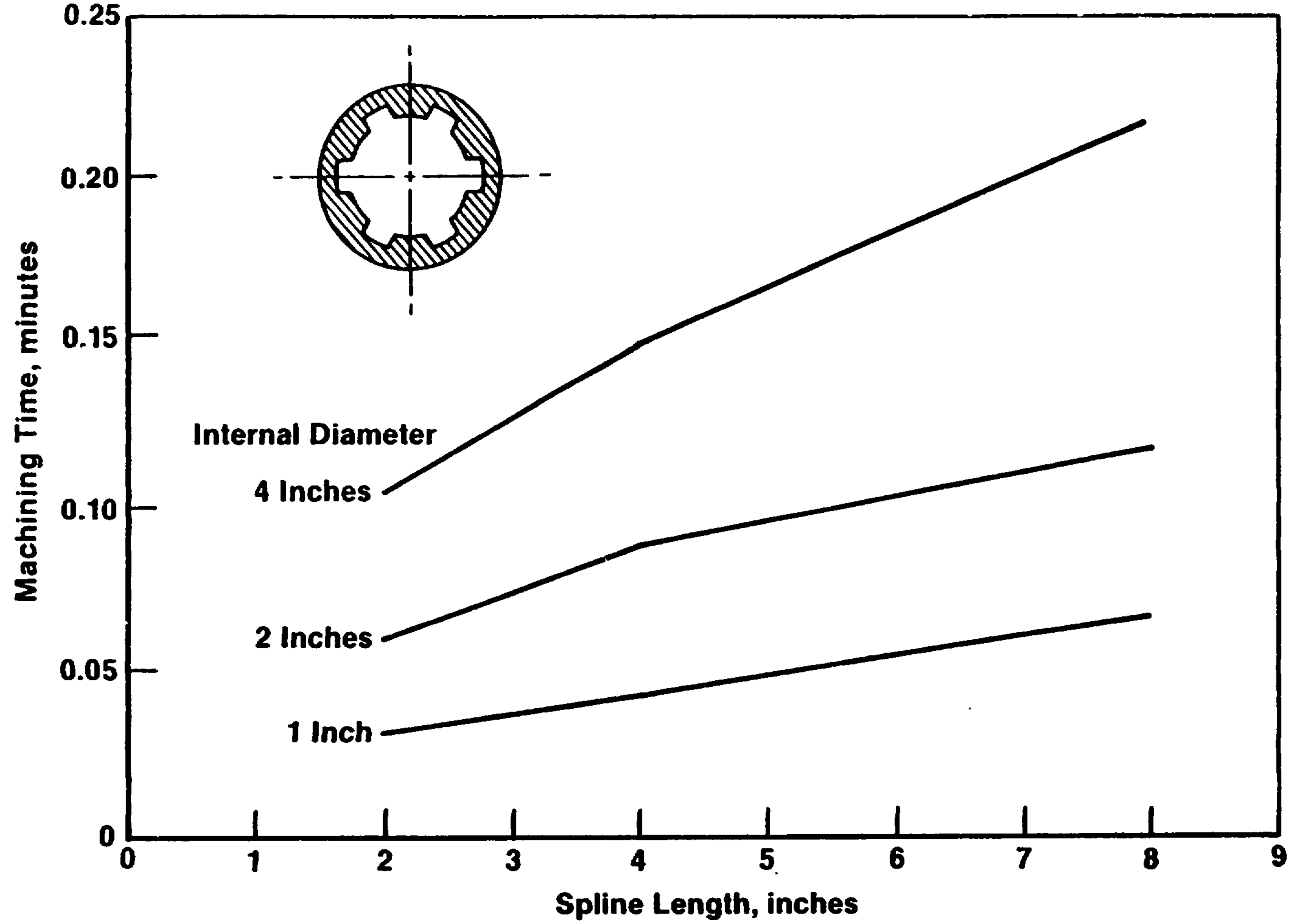


CED-M/C-63

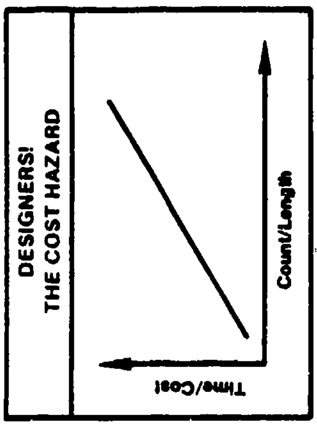
EFFECT OF NUMBER AND LENGTH OF INTERNAL SPLINES FOR:

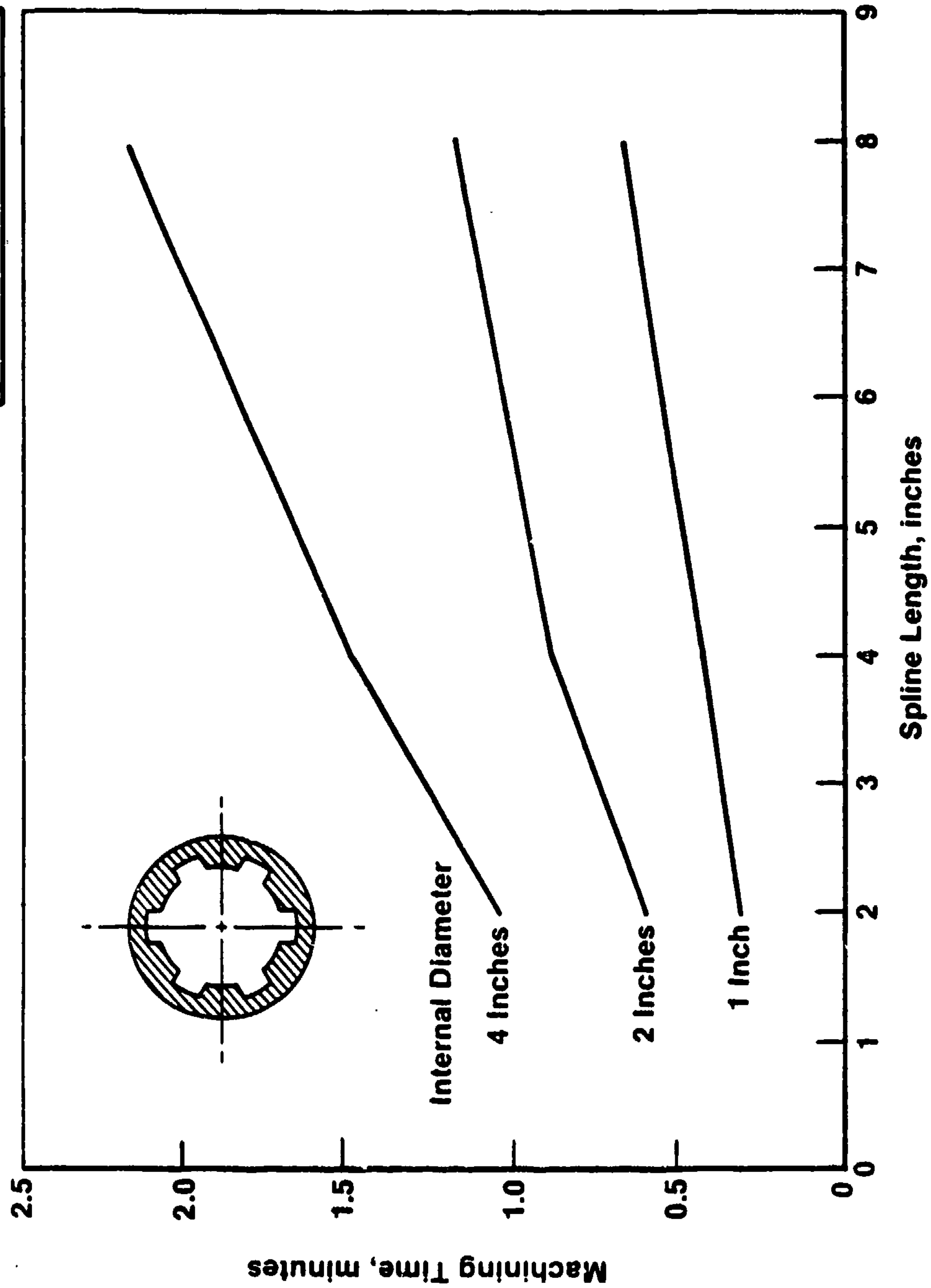
ALUMINUM



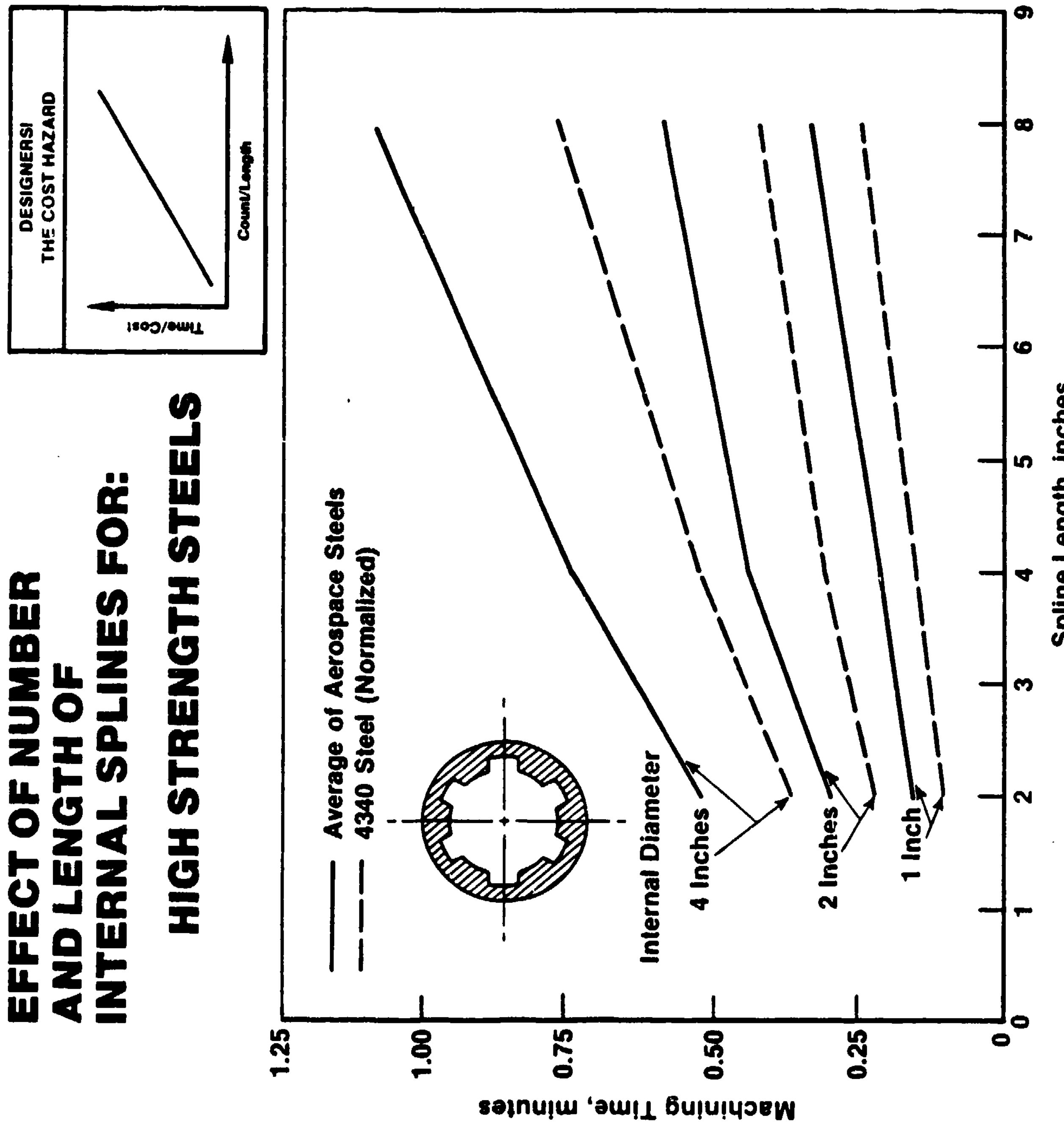


EFFECT OF NUMBER AND LENGTH OF INTERNAL SPLINES FOR: TITANIUM





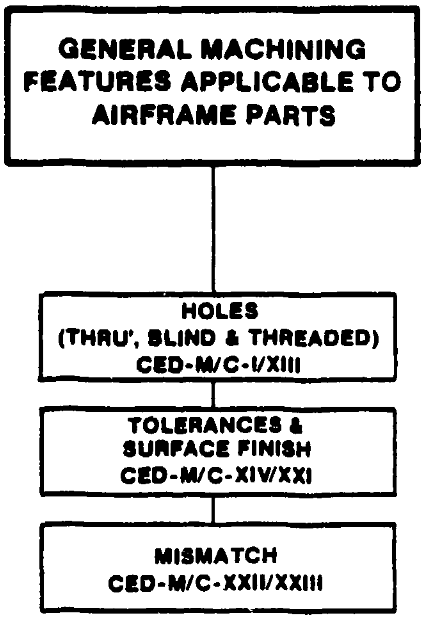
CED-M/C-65


EFFECT OF NUMBER AND LENGTH OF INTERNAL SPLINES FOR:
HIGH STRENGTH STEELS
DESIGNERS!
THE COST HAZARD
Time/Cost
Count/Length
Average of Aerospace Steels
4340 Steel (Normalized)
Internal Diameter
4 Inches
2 Inches
1 Inch
Machining Time, minutes
0
0.25
0.50
0.75
1.00
1.25
Spline Length, inches
0
1
2
3
4
5
6
7
8
9

CED-M/C-66

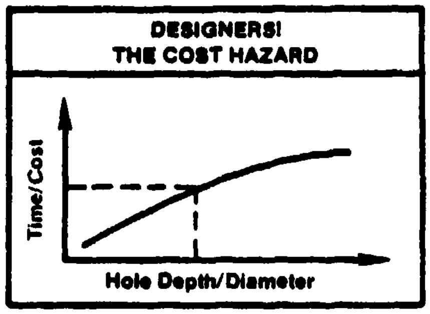
FORMAT SELECTION AID

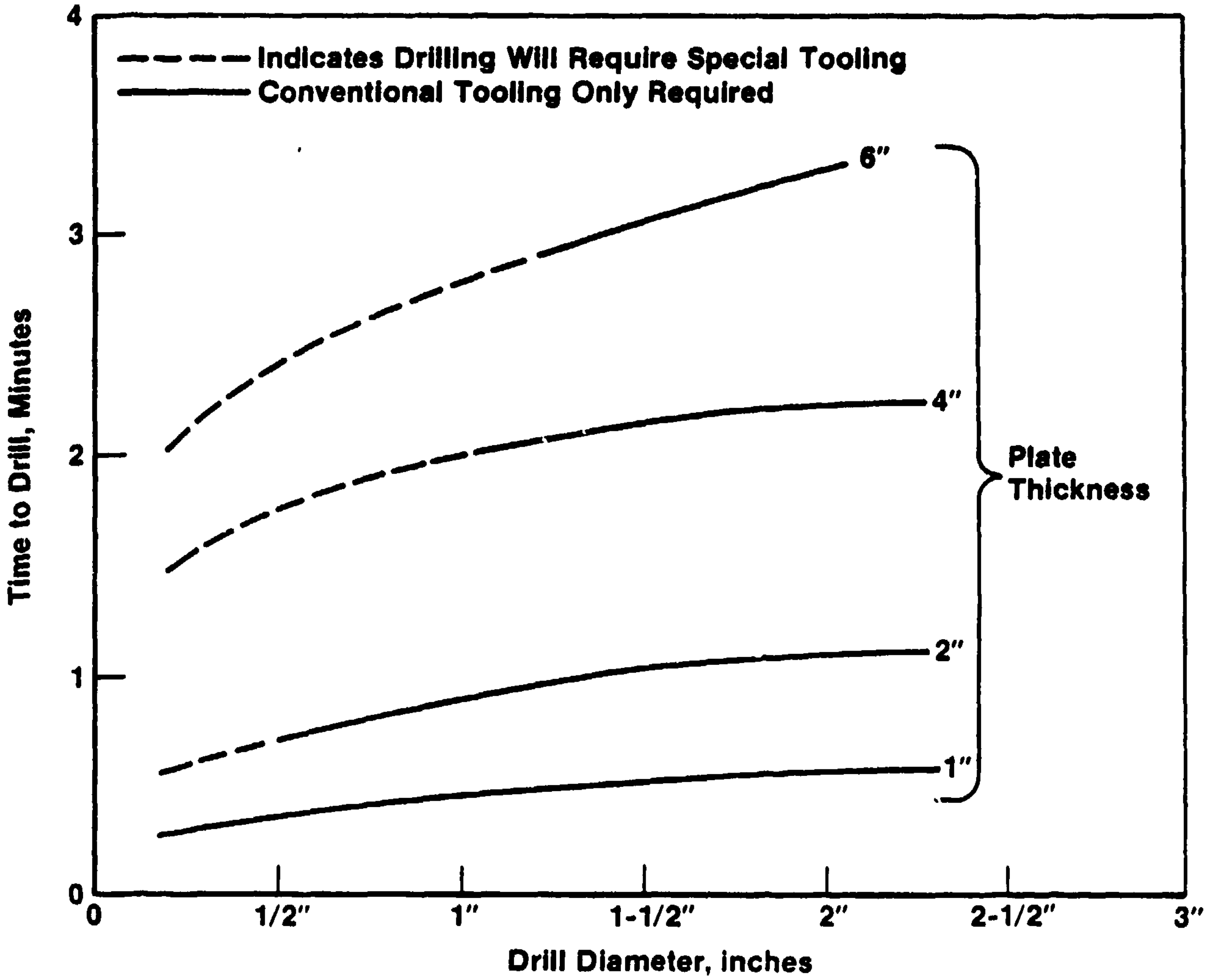
MACHINING OF METALS



TIME REQUIRED TO DRILL 10 HOLES IN:

ALUMINUM PLATE

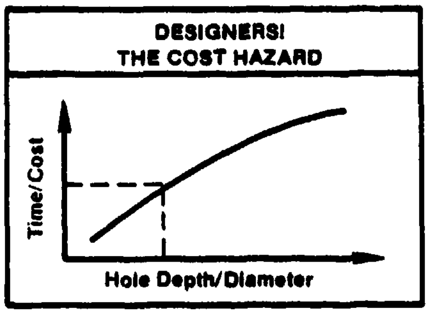


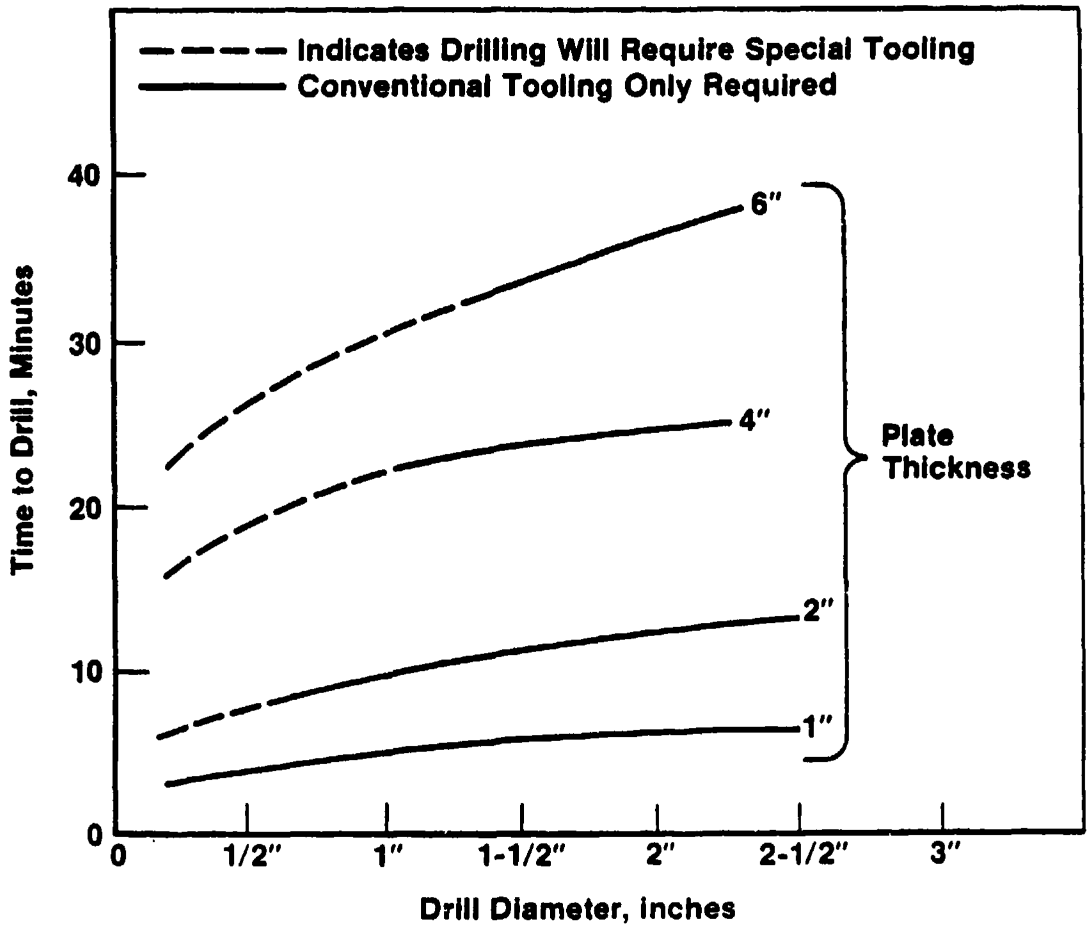


CED-M/C-I

TIME REQUIRED TO DRILL 10 HOLES IN:

TITANIUM PLATE

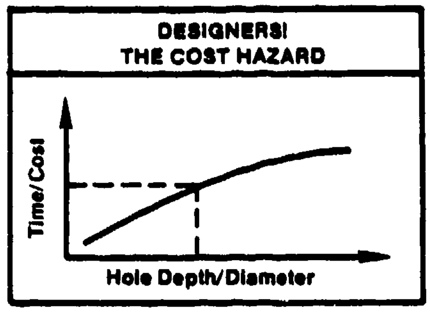


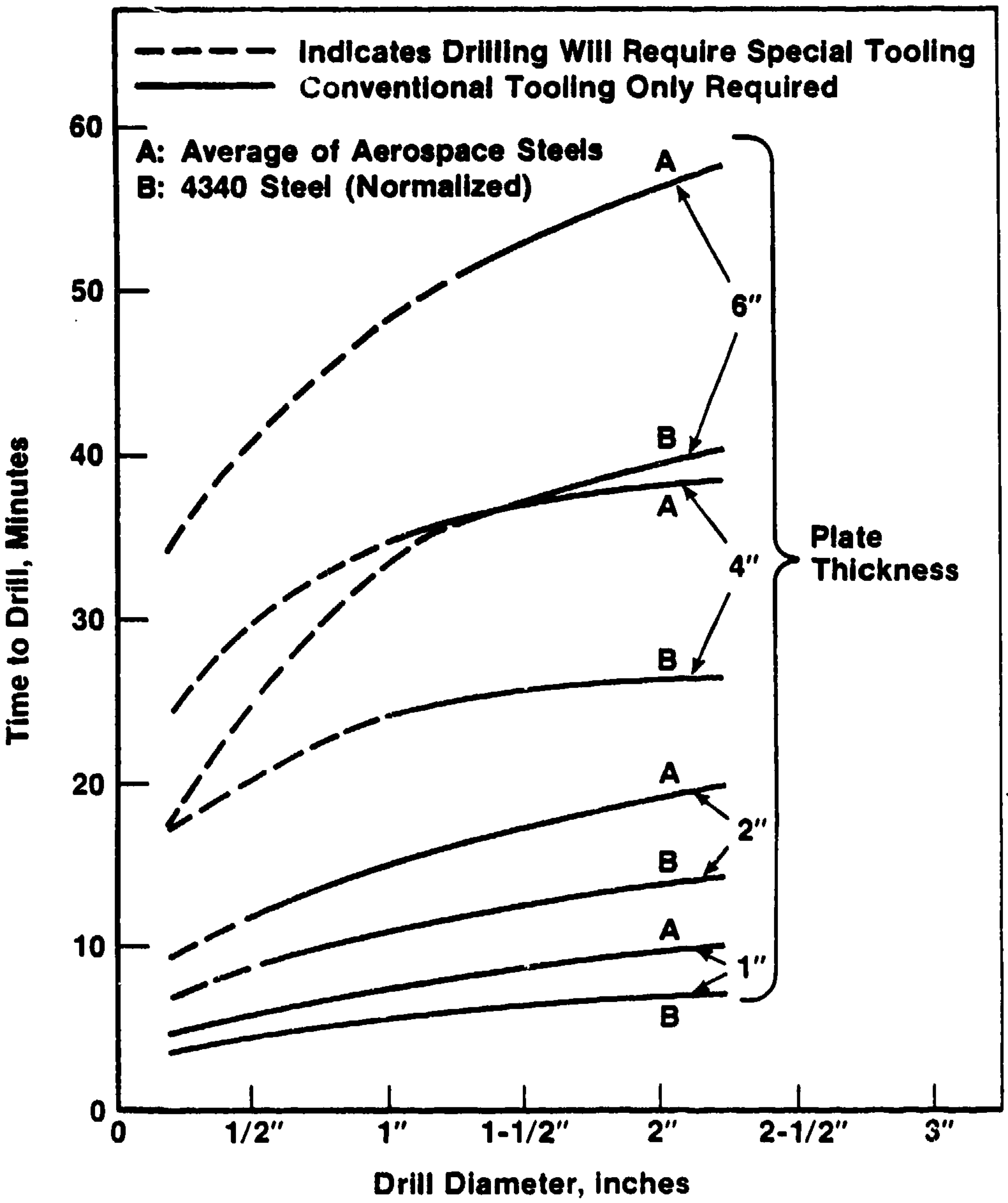


CED-M/C-II

TIME REQUIRED TO DRILL 10 HOLES IN:

HIGH STRENGTH STEEL PLATE

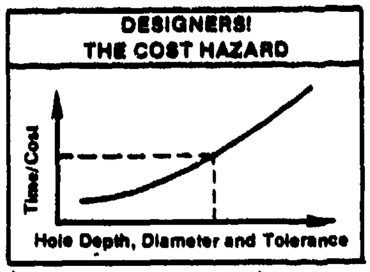




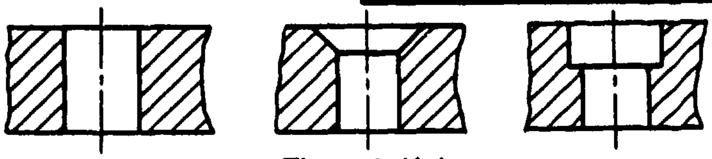
CED-M/C-III

FTR450261000
6 Mar 1985

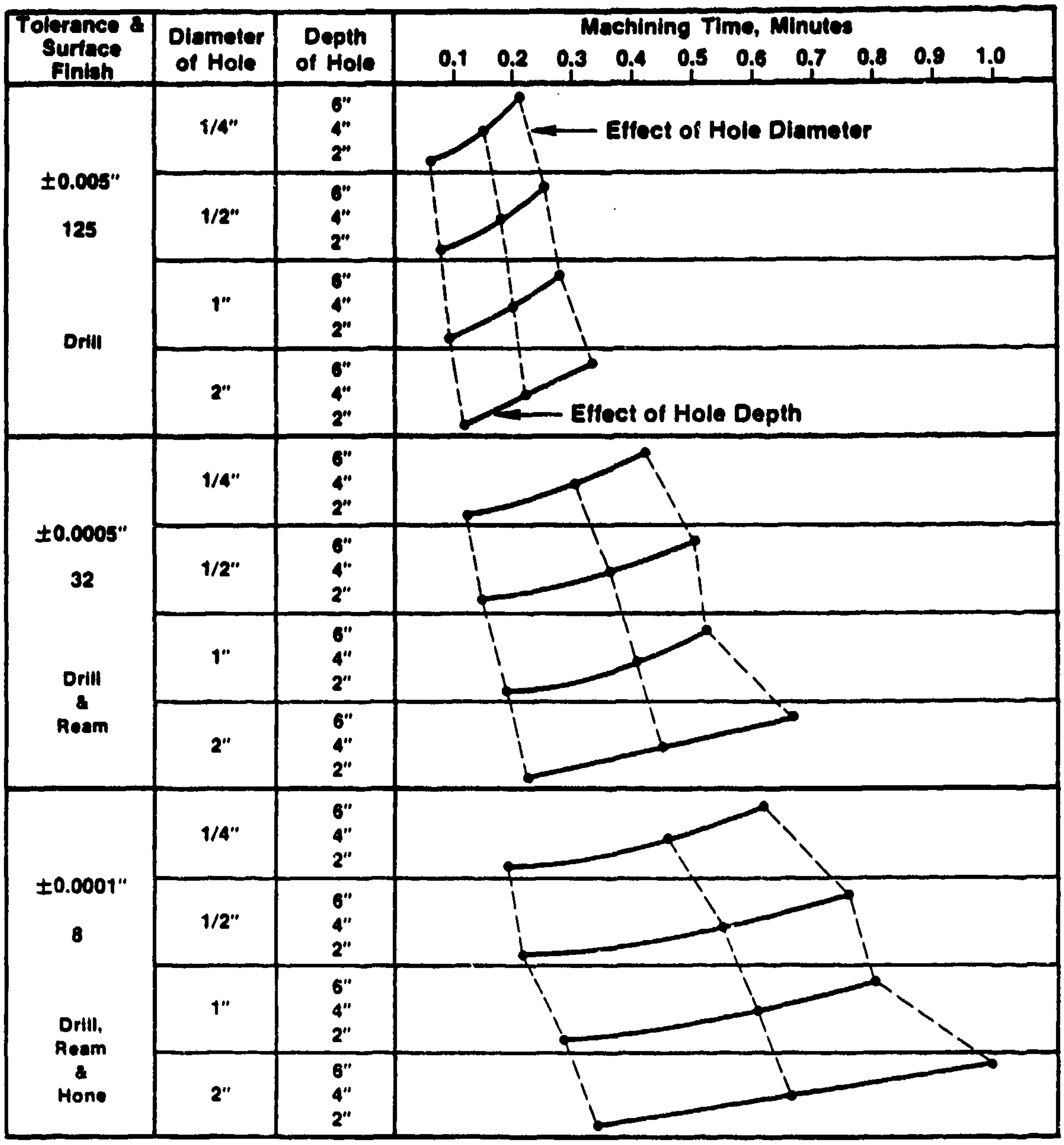
EFFECT OF HOLE DIMENSIONS, TOLERANCE AND SURFACE FINISH ON MACHINING TIME



ALUMINUM

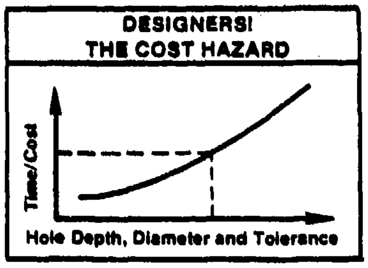


Through Hole

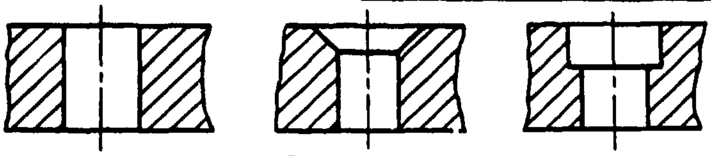


CED-M/C-IV

EFFECT OF HOLE DIMENSIONS, TOLERANCE AND SURFACE FINISH ON MACHINING TIME

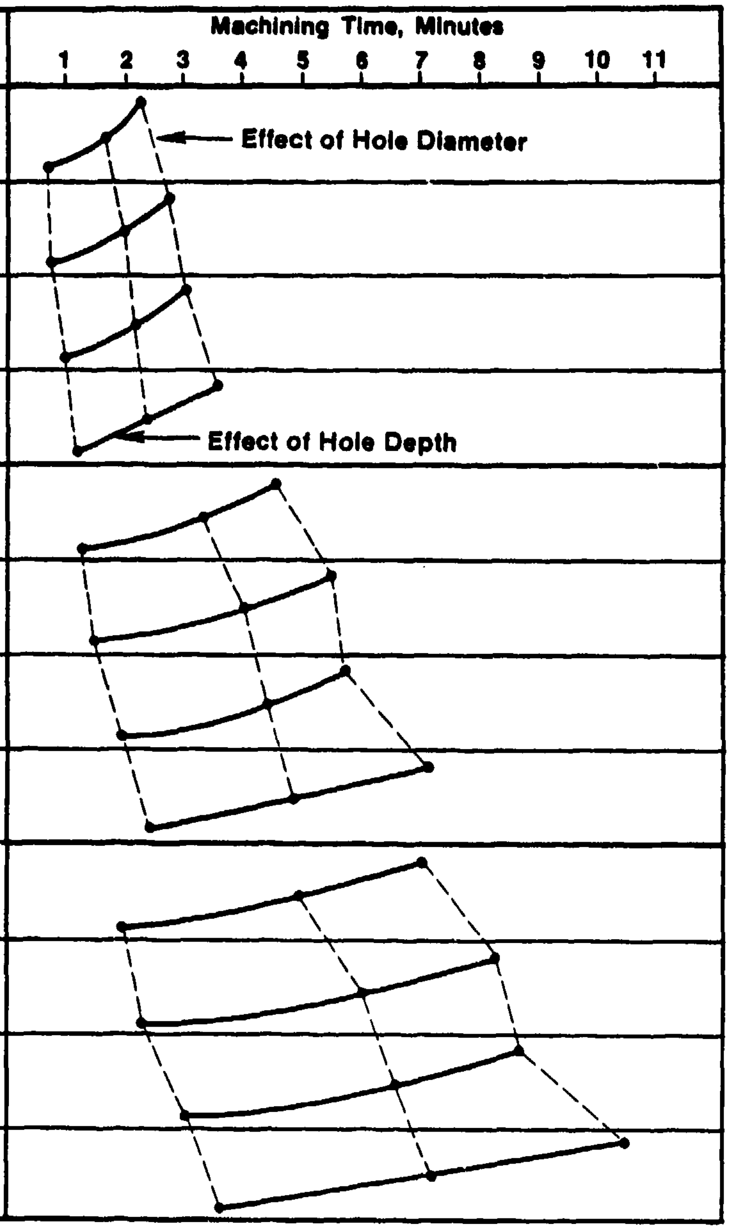


TITANIUM



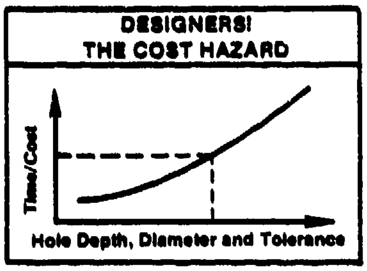
Through Hole

Tolerance & Surface Finish	Diameter of Hole	Depth of Hole	Machining Time, Minutes
±0.005" 125 Drill	1/4"	6" 4" 2"	
	1/2"	6" 4" 2"	
	1"	6" 4" 2"	
	2"	6" 4" 2"	
±0.0005" 32 Drill & Ream	1/4"	6" 4" 2"	
	1/2"	6" 4" 2"	
	1"	6" 4" 2"	
	2"	6" 4" 2"	
±0.0001" 8 Drill, Ream & Hone	1/4"	6" 4" 2"	
	1/2"	6" 4" 2"	
	1"	6" 4" 2"	
	2"	6" 4" 2"	

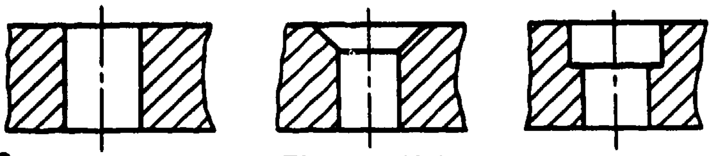


CED-M/C-V

EFFECT OF HOLE DIMENSIONS, TOLERANCE AND SURFACE FINISH ON MACHINING TIME

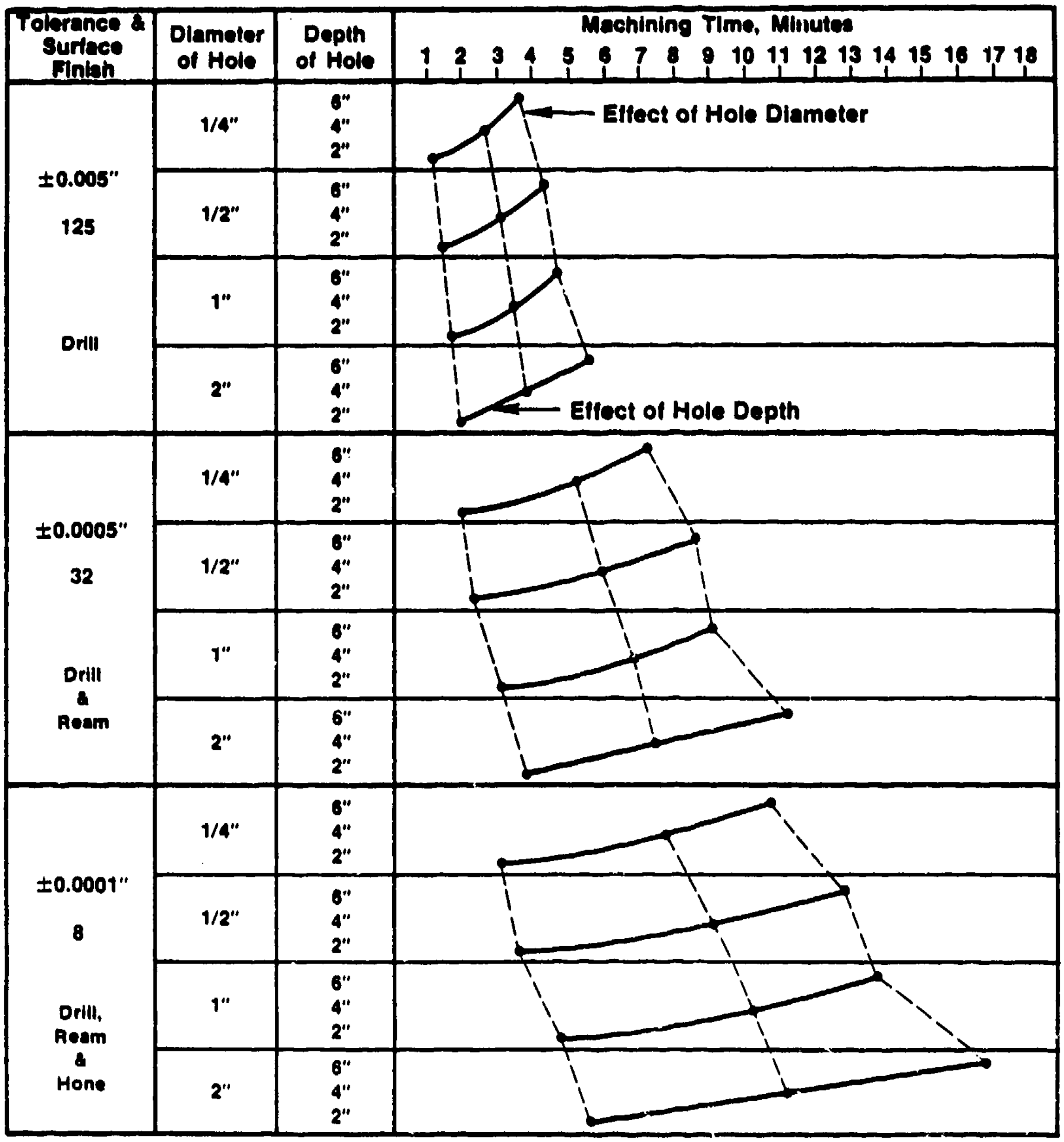


HIGH STRENGTH STEELS



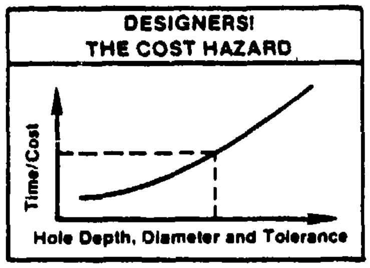
Through Hole

Average of Aerospace Steels

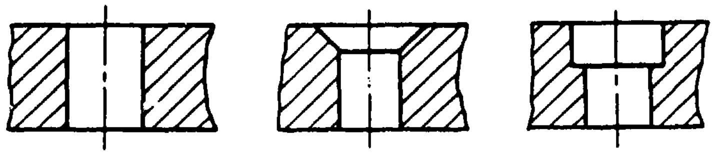


CED-M/C-VI

EFFECT OF HOLE DIMENSIONS, TOLERANCE AND SURFACE FINISH ON MACHINING TIME

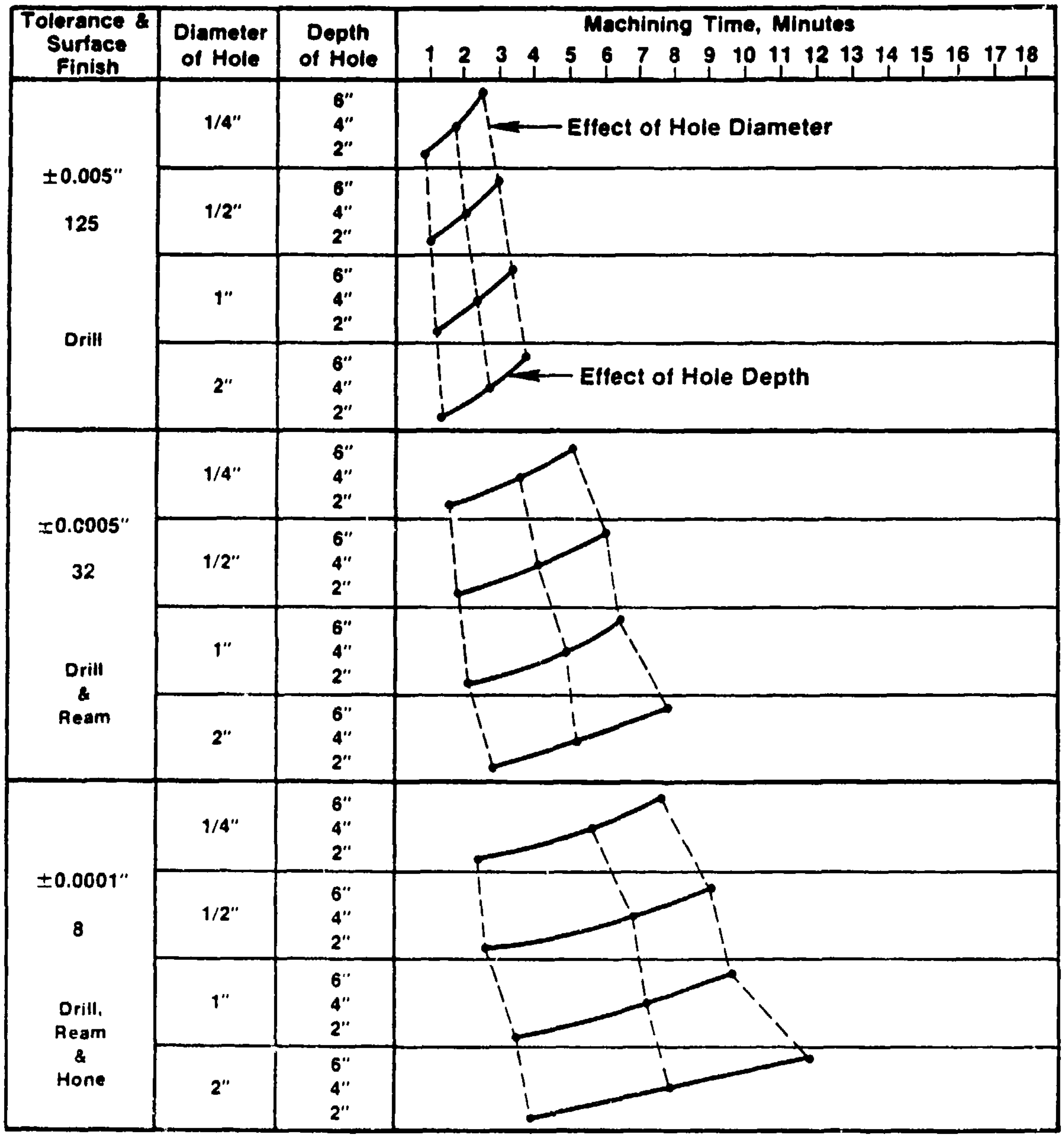


HIGH STRENGTH STEELS

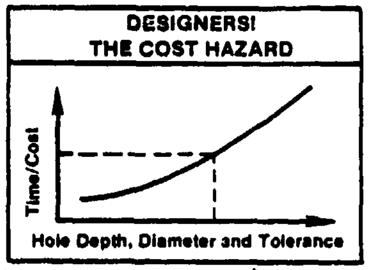


Through Hole

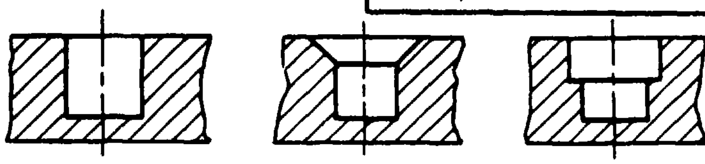
4340 Steel (Normalized)



EFFECT OF HOLE DIMENSIONS, TOLERANCE AND SURFACE FINISH ON MACHINING TIME

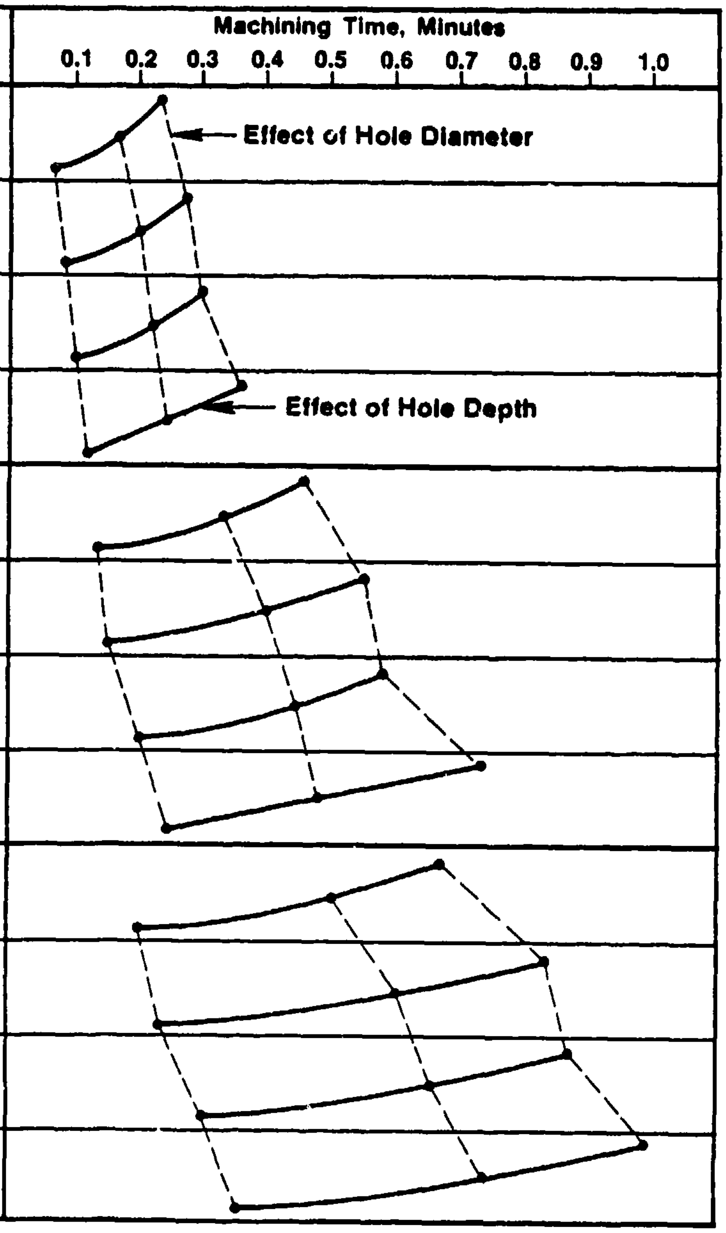


ALUMINUM

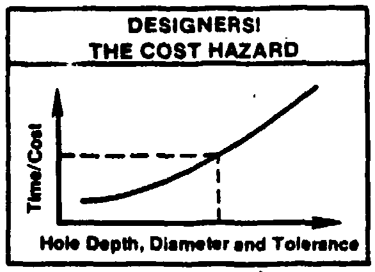


Blind Hole

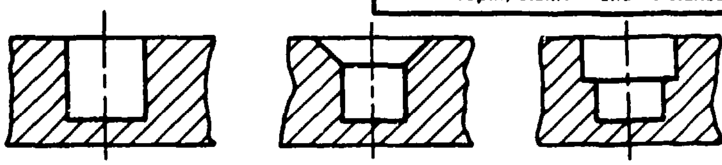
Tolerance & Surface Finish	Diameter of Hole	Depth of Hole
±0.005" 125 Drill	1/4"	6" 4" 2"
	1/2"	6" 4" 2"
	1"	6" 4" 2"
	2"	6" 4" 2"
±0.0005" 32 Drill & Ream	1/4"	6" 4" 2"
	1/2"	6" 4" 2"
	1"	6" 4" 2"
	2"	6" 4" 2"
±0.0001" 8 Drill, Ream & Hone	1/4"	6" 4" 2"
	1/2"	6" 4" 2"
	1"	6" 4" 2"
	2"	6" 4" 2"



EFFECT OF HOLE DIMENSIONS, TOLERANCE AND SURFACE FINISH ON MACHINING TIME

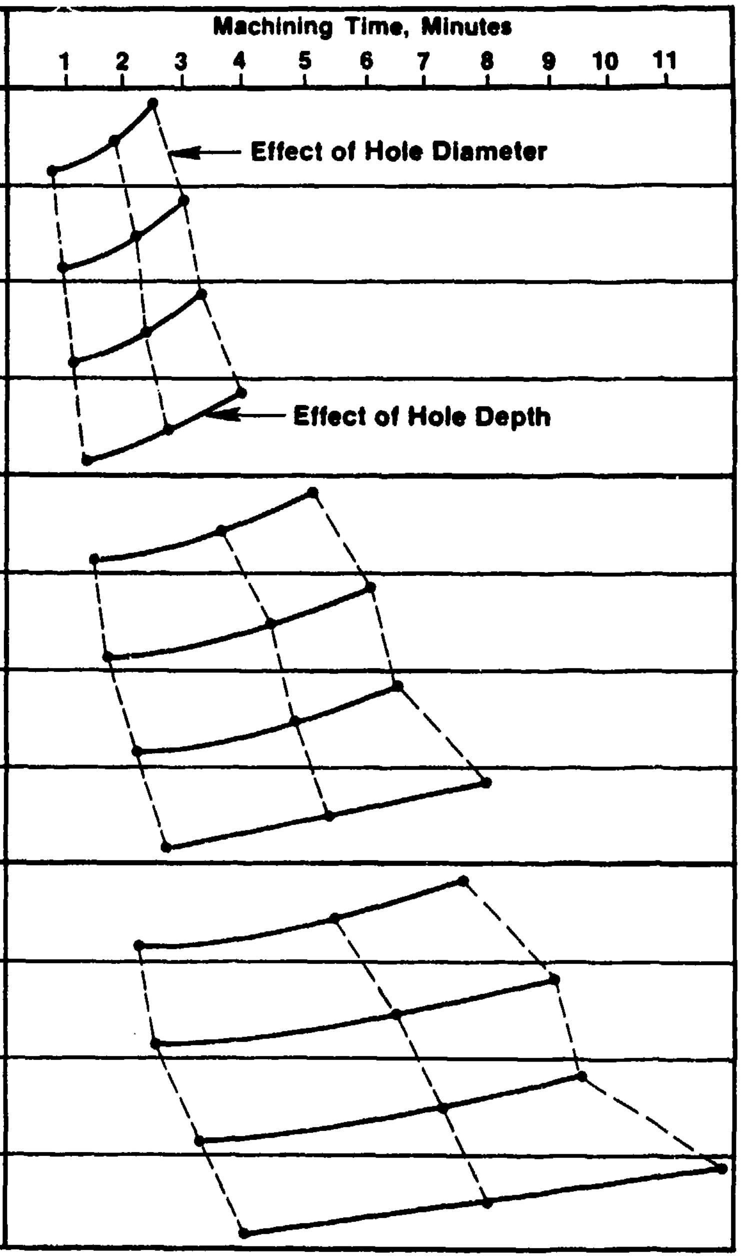


TITANIUM



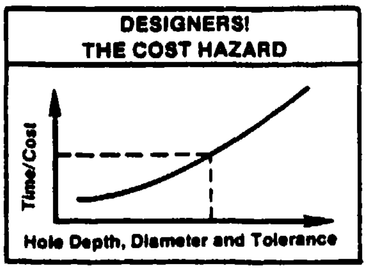
Blind Hole

Tolerance & Surface Finish	Diameter of Hole	Depth of Hole	Machining Time, Minutes
±0.005" 125 Drill	1/4"	6" 4" 2"	
	1/2"	6" 4" 2"	
	1"	6" 4" 2"	
	2"	6" 4" 2"	
±0.0005' 32 Drill & Ream	1/4"	6" 4" 2"	
	1/2"	6" 4" 2"	
	1"	6" 4" 2"	
	2"	6" 4" 2"	
±0.0001" 8 Drill, Ream & Hone	1/4"	6" 4" 2"	
	1/2"	6" 4" 2"	
	1"	6" 4" 2"	
	2"	6" 4" 2"	

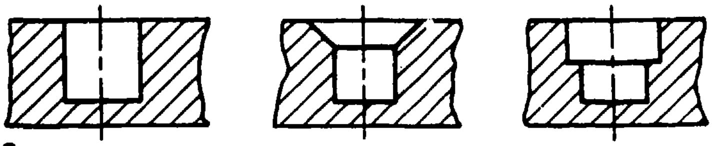


CED-M/C-IX

EFFECT OF HOLE DIMENSIONS, TOLERANCE AND SURFACE FINISH ON MACHINING TIME

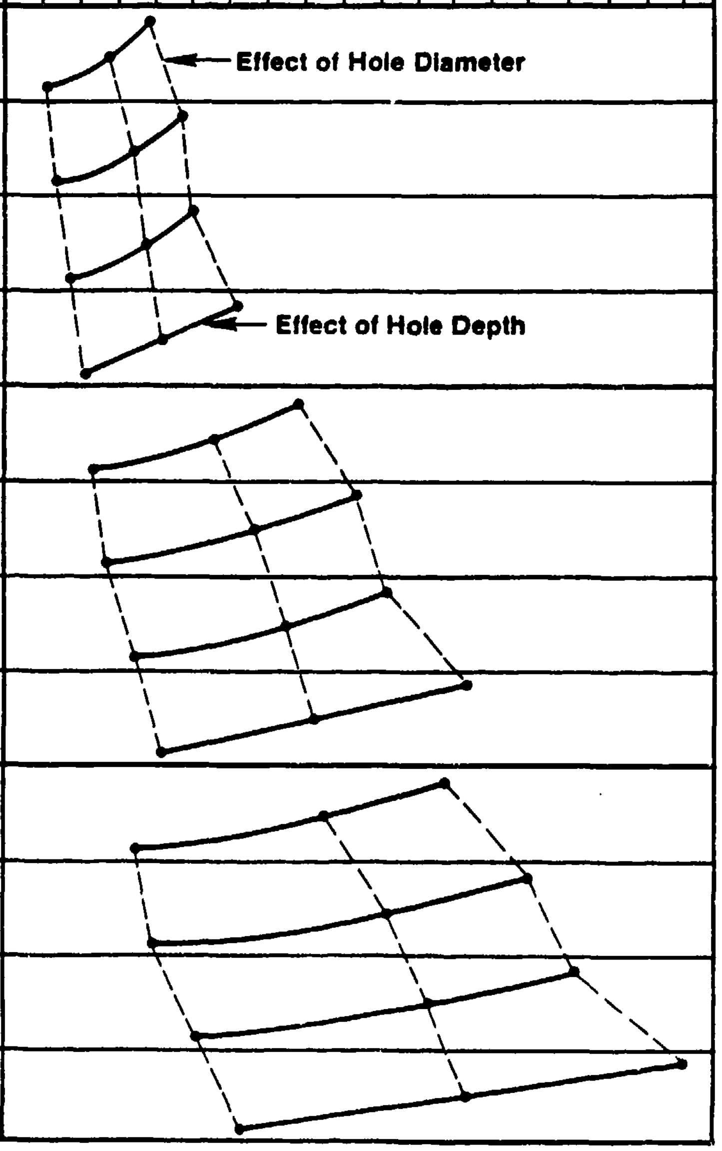


HIGH STRENGTH STEELS



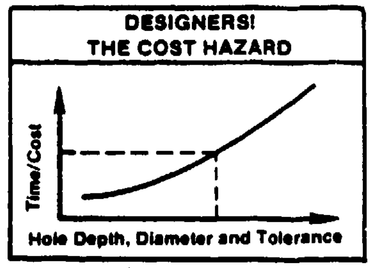
Average of Aerospace Steels

Tolerance & Surface Finish	Diameter of Hole	Depth of Hole	Machining Time, Minutes 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
±0.005" 125 Drill	1/4"	6" 4" 2"	
	1/2"	6" 4" 2"	
	1"	6" 4" 2"	
	2"	6" 4" 2"	
±0.0005" 32 Drill & Ream	1/4"	6" 4" 2"	
	1/2"	6" 4" 2"	
	1"	6" 4" 2"	
	2"	6" 4" 2"	
±0.0001" 8 Drill, Ream & Hone	1/4"	6" 4" 2"	
	1/2"	6" 4" 2"	
	1"	6" 4" 2"	
	2"	6" 4" 2"	

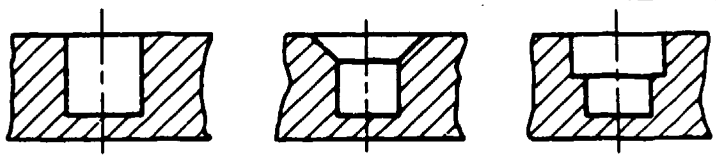


CED-M/C-X

EFFECT OF HOLE DIMENSIONS, TOLERANCE AND SURFACE FINISH ON MACHINING TIME

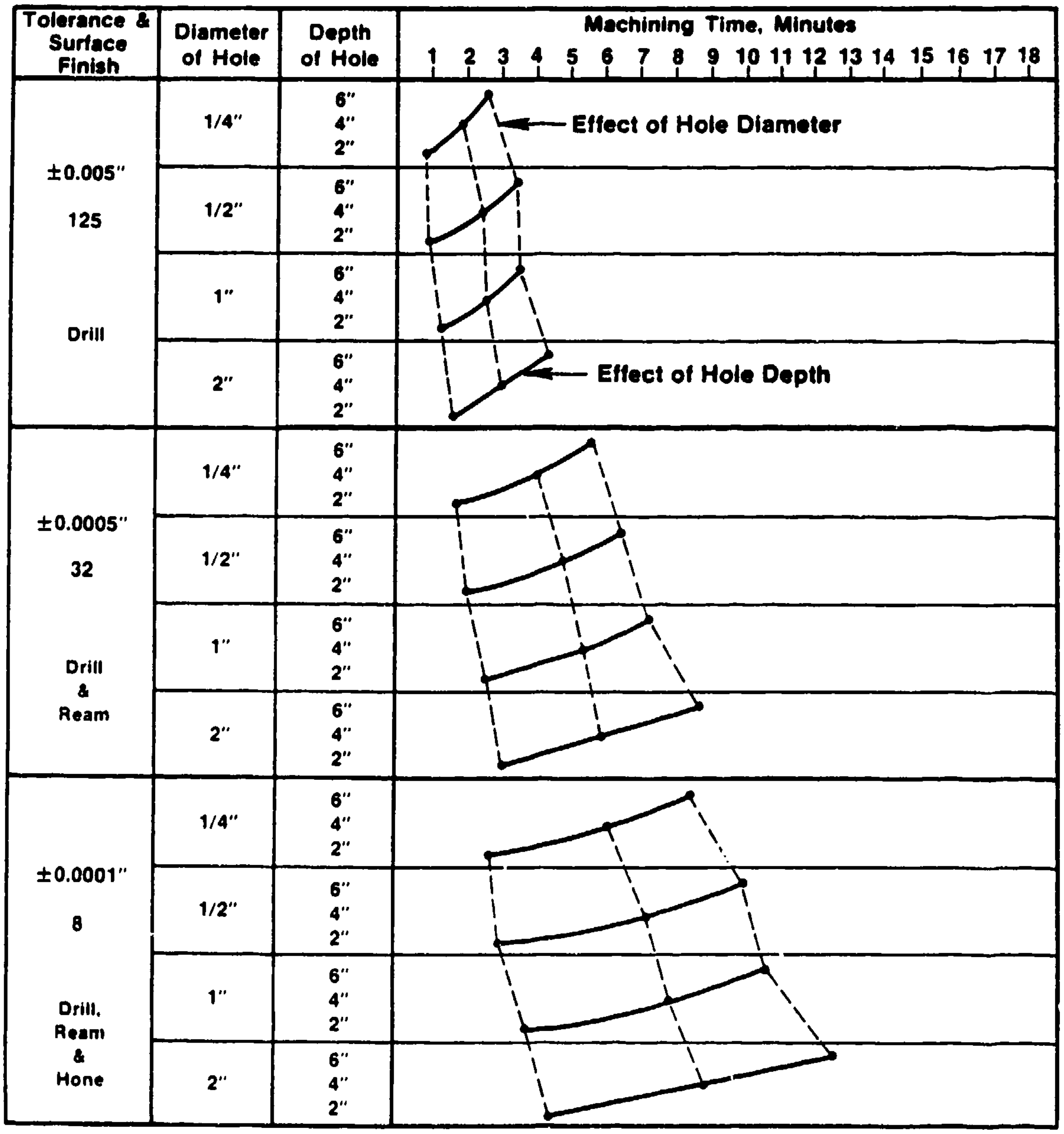


HIGH STRENGTH STEELS



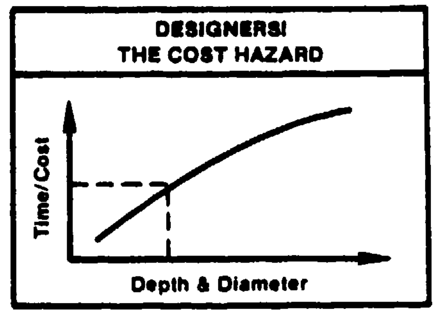
Blind Hole

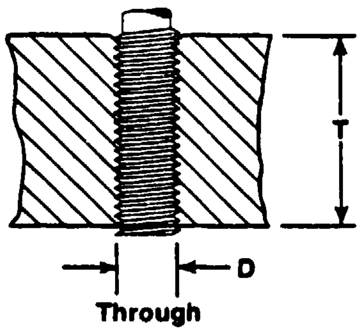
4340 Steel (Normalized)



EFFECT OF THREADED HOLES

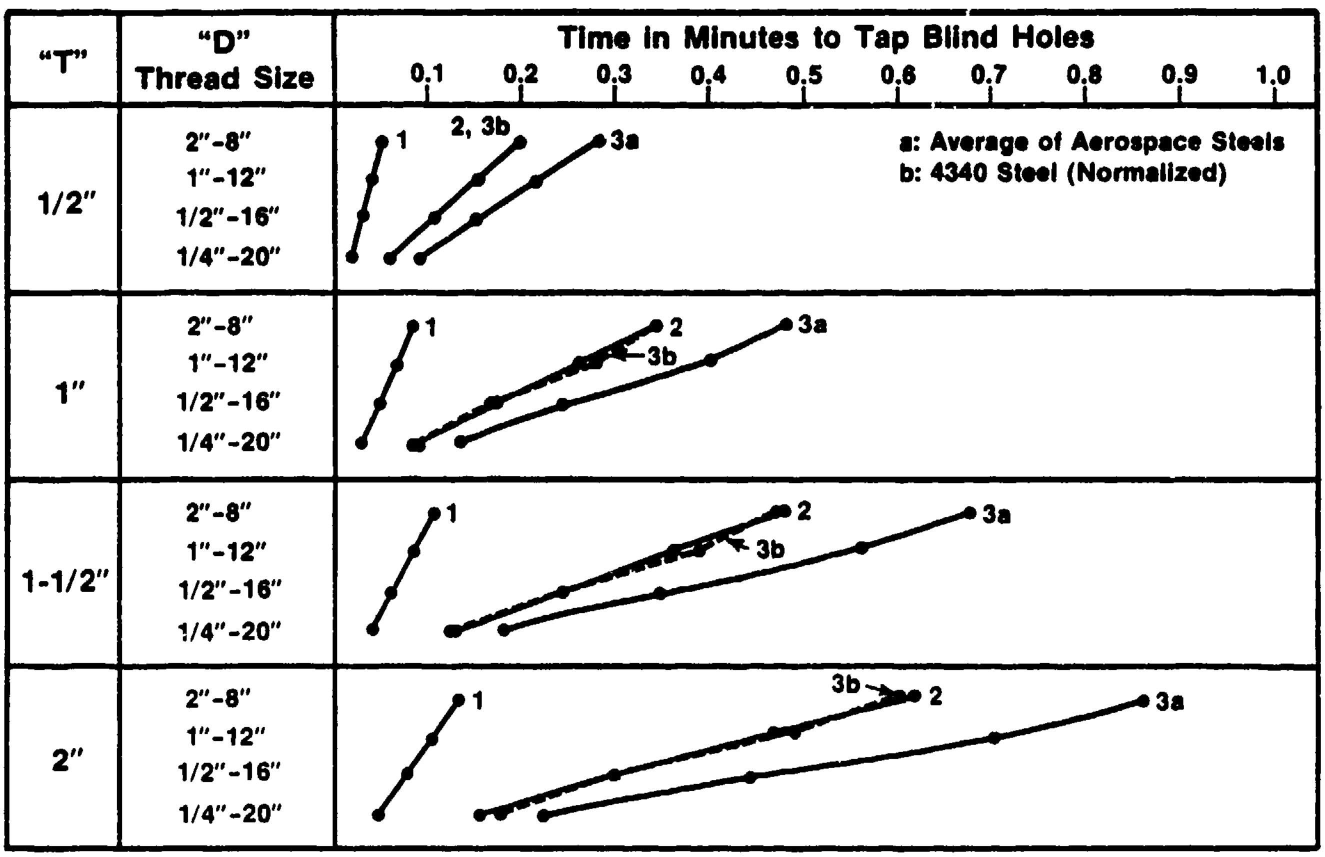
THROUGH HOLES ONLY





Where:
- T = Thickness Through Part or Depth of Thread in Blind Hole
- D = Diameter of Thread or Thread Size

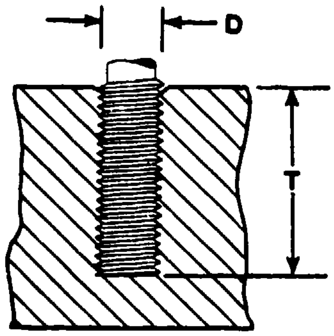
Material: 1 = Aluminum
2 = Titanium
3 = High Strength Steel



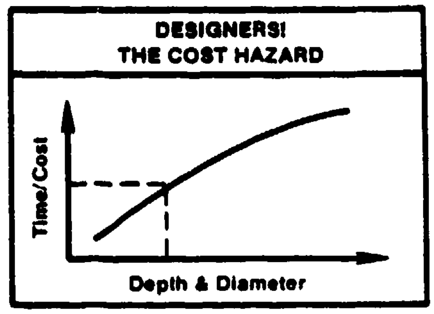
CED-M/C-XII

EFFECT OF THREADED HOLES

BLIND HOLES ONLY

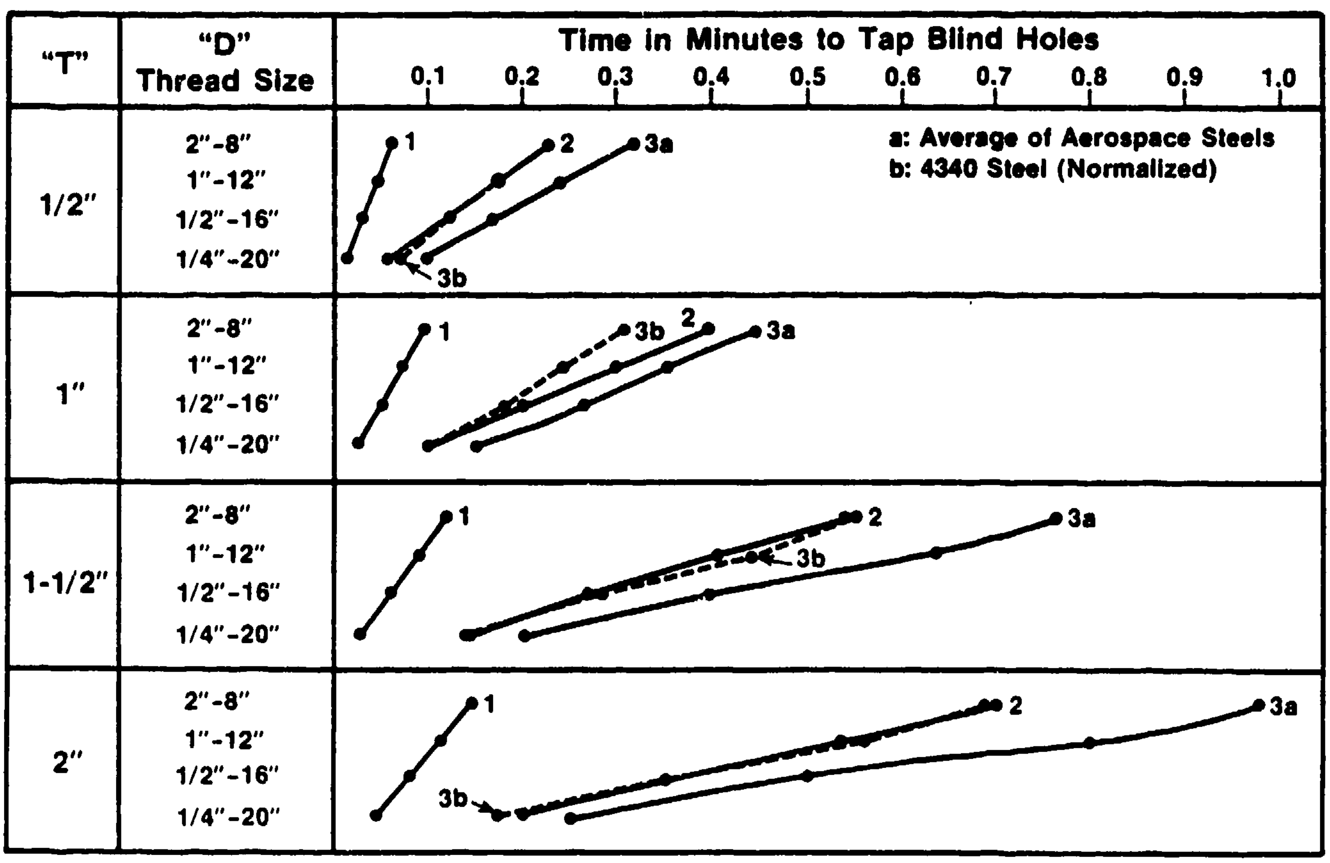


Blind



Where:
T = Thickness Through Part or Depth of Thread in Blind Hole
D = Diameter of Thread or Thread Size

Material: 1 = Aluminum
2 = Titanium
3 = High Strength Steel

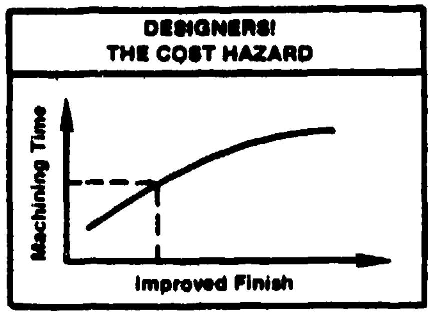


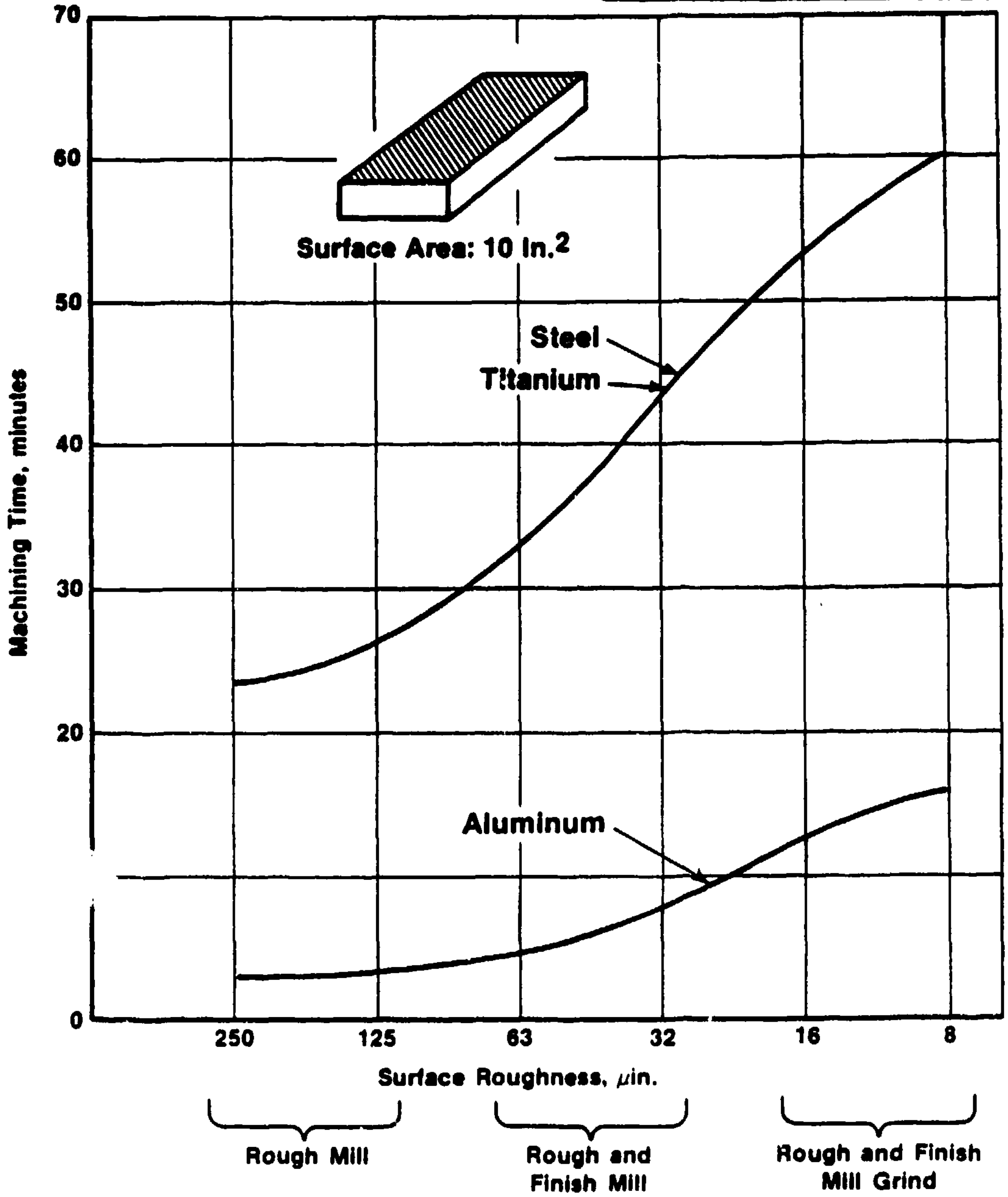
Scale = Factor of 1.1 x Through Holes

CED-M/C-XIII

EFFECT OF SURFACE ROUGHNESS REQUIREMENTS ON MACHINING TIME FOR:

FLAT SURFACE

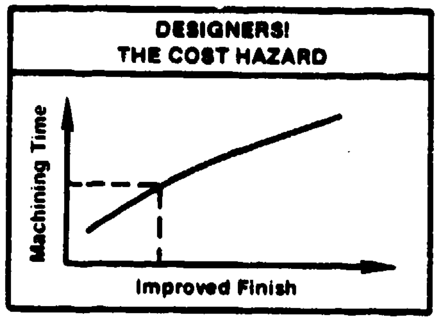


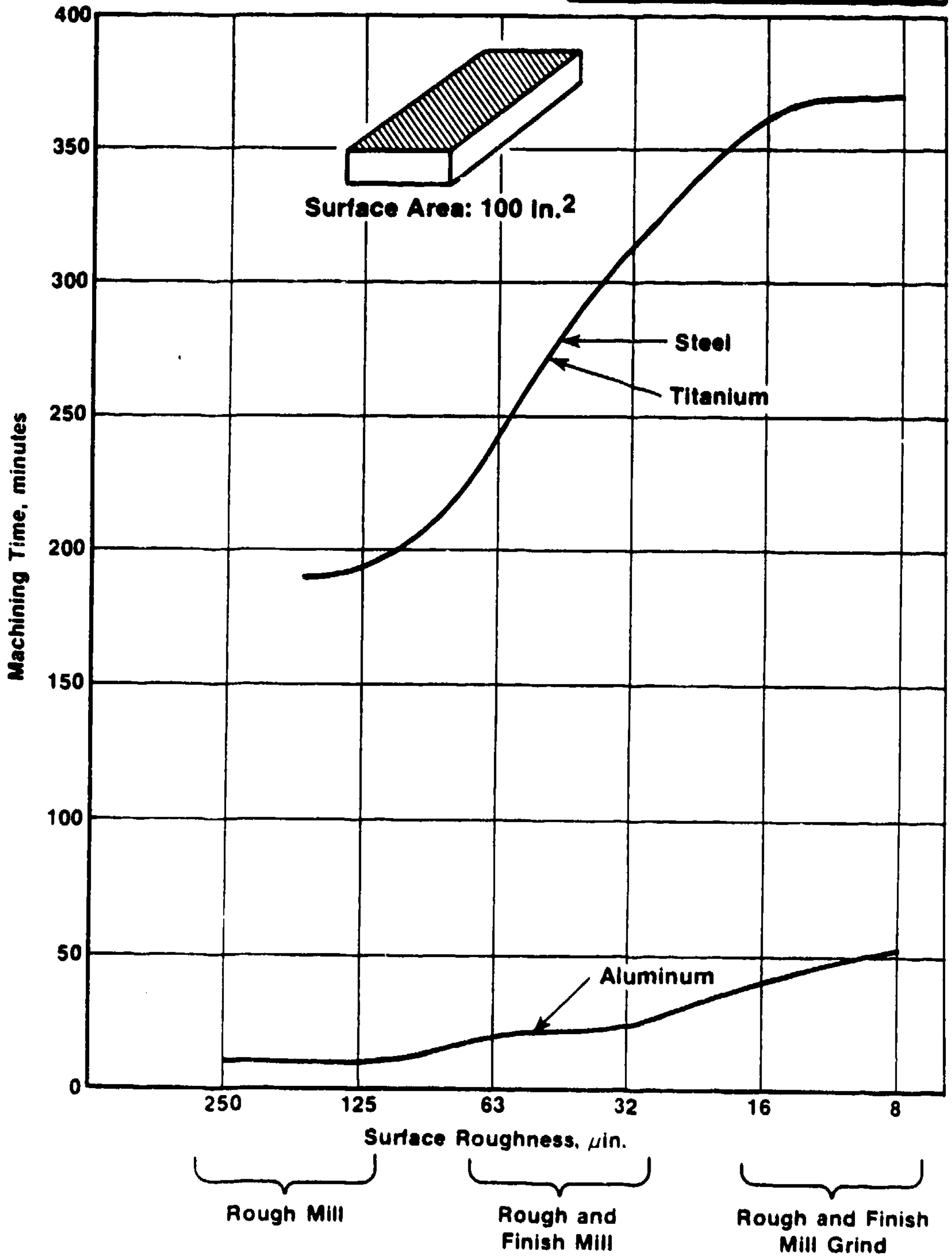


CED-M/C-XIV

EFFECT OF SURFACE ROUGHNESS REQUIREMENTS ON MACHINING TIME FOR:

FLAT SURFACE

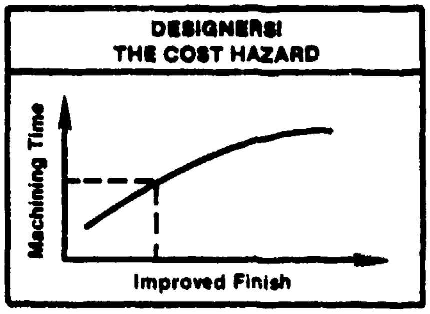


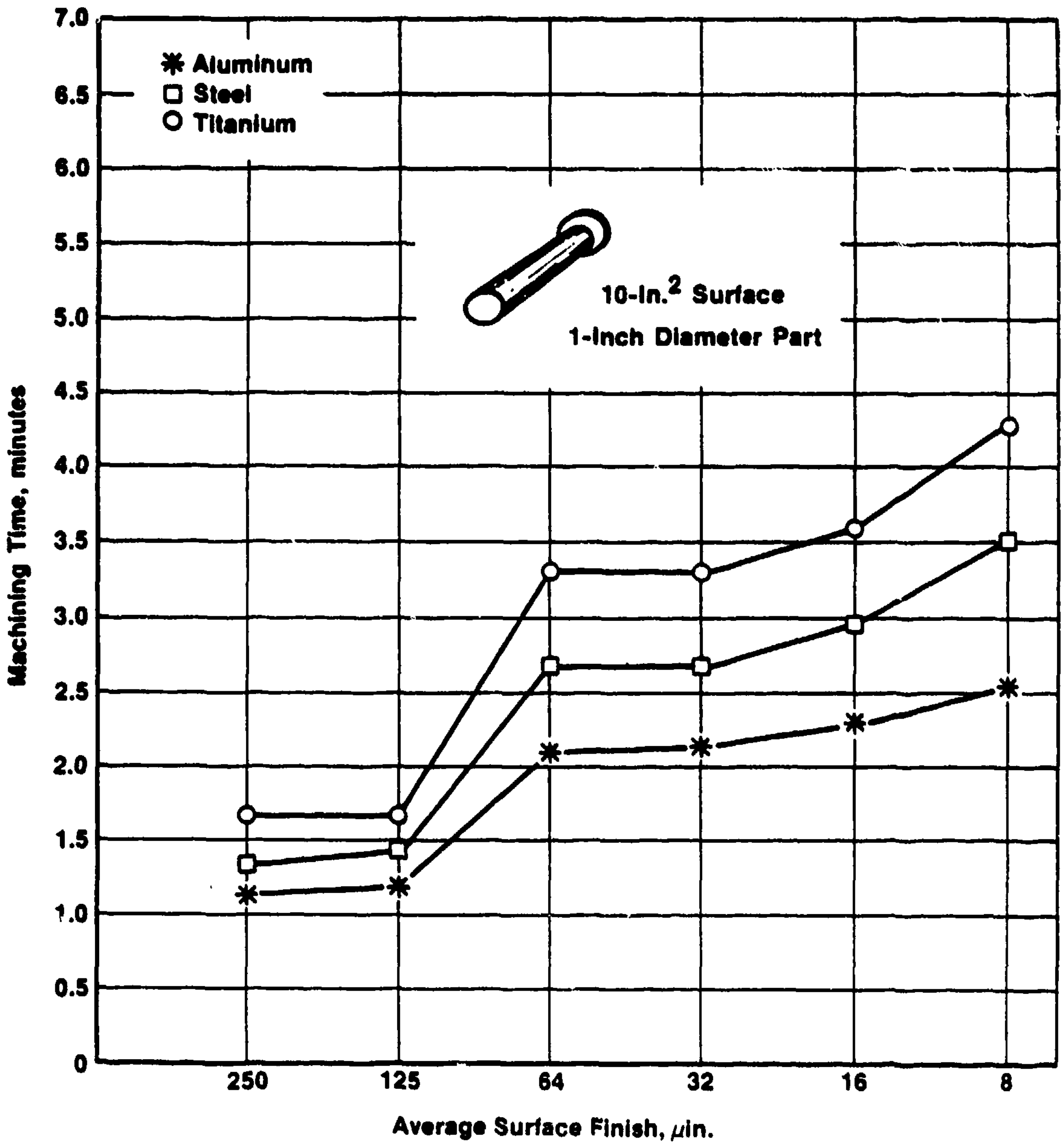


CED-M/C-XV

EFFECT OF SURFACE ROUGHNESS REQUIREMENTS ON MACHINING TIME FOR:

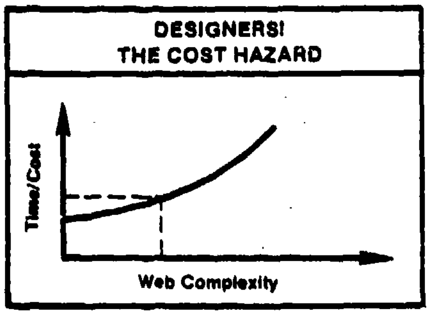
CYLINDRICAL SURFACE



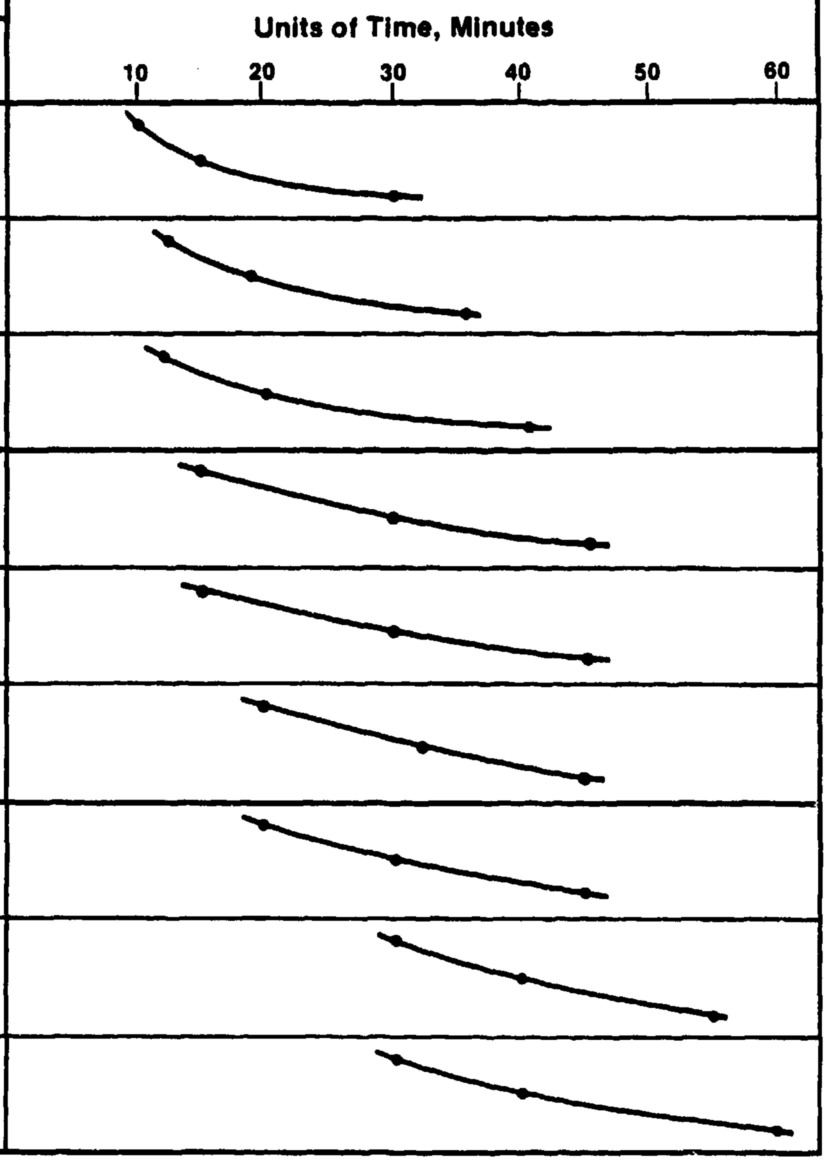


CED-M/C-XVI

WEBS: EFFECT OF TOLERANCE AND SURFACE FINISH FOR ALUMINUM, TITANIUM, AND STEEL



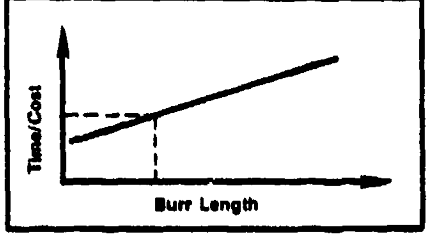
Web Complexity Factors			
Web Thickness	Dimensional Tolerance	Surface Finish	Units of Time, Minutes
1/2"	±0.010"	125 64 32	
	±0.005"	125 64 32	
	±0.001"	125 64 32	
1/4"	±0.010"	125 64 32	
	±0.005"	125 64 32	
	±0.001"	125 64 32	
1/8"	±0.010"	125 64 32	
	±0.005"	125 64 32	
	±0.001"	125 64 32	



CED-M/C-XVII

TIME REQUIRED TO HAND DEBURR AND EDGE BREAK

**DESIGNERS!
THE COST HAZARD**



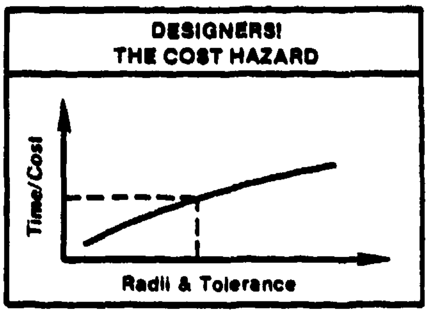
Operation	Burr Size	Break Size	Tolerance Requirements	Time in Minutes (1.0 … 2.0)
Deburring Only	Small Medium Large	—	—	
Deburring & Edge Breaking	SMALL	Small	Open Medium Close	
		Medium	Open Medium Close	
		Large	Open Medium Close	
	MEDIUM	Small	Open Medium Close	
		Medium	Open Medium Close	
		Large	Open Medium Close	
	LARGE	Small Medium Large	Open Medium Close	
		Small Medium Large	Open Medium Close	
		Small Medium Large	Open Medium Close	

Small Burr = 0.004" or Less
Medium Burr = 0.005"-0.015"
Large Burr = 0.015"-Up

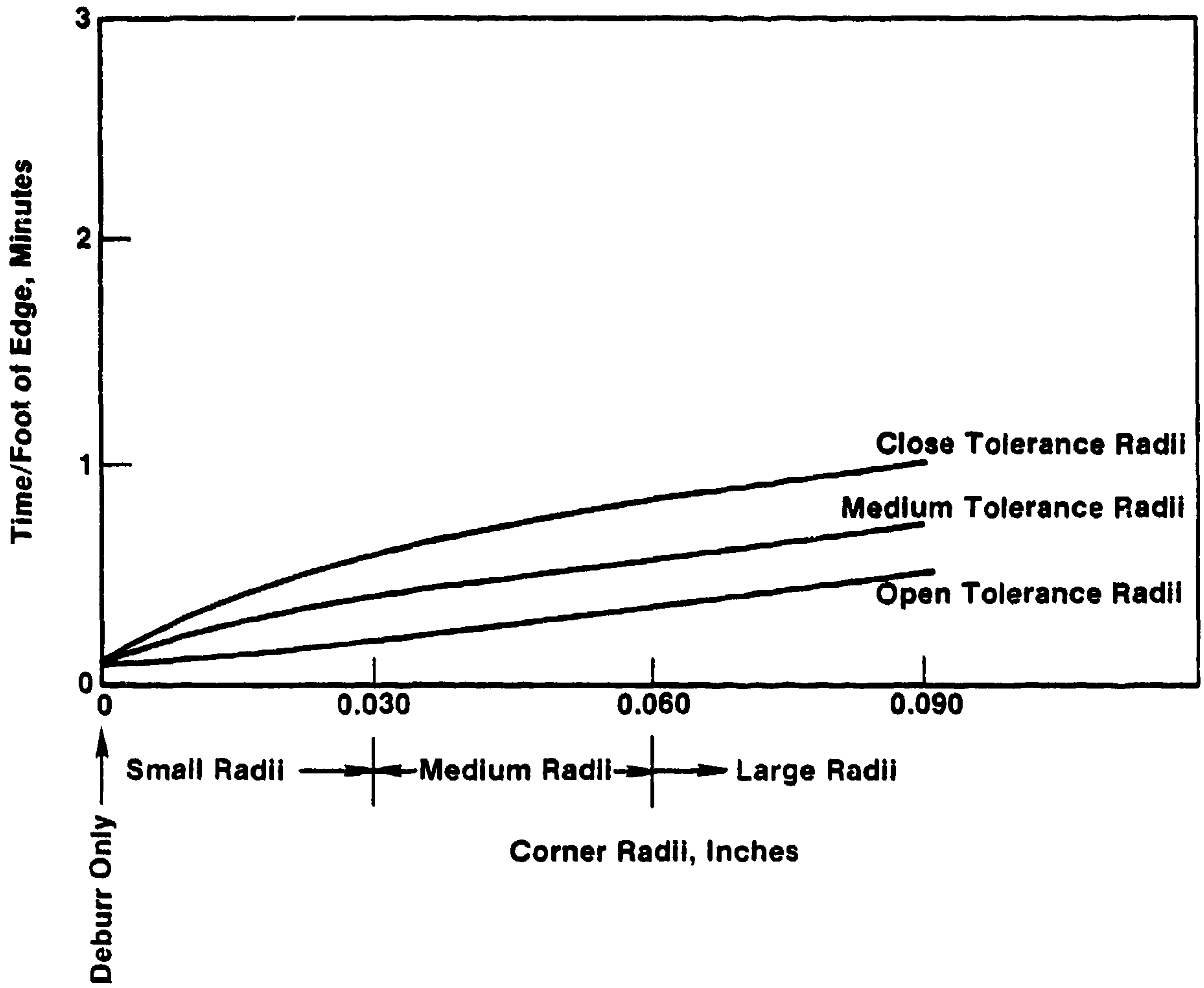
Small Radius Up to 0.030"
Medium Radius 0.030"-0.060"
Large Radius 0.060"-0.090"

CED-M/C-XVIII

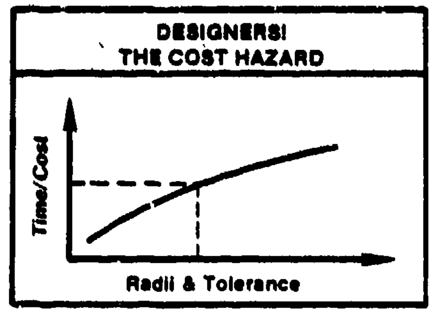
TIME REQUIRED TO HAND DEBURR AND EDGE BREAK



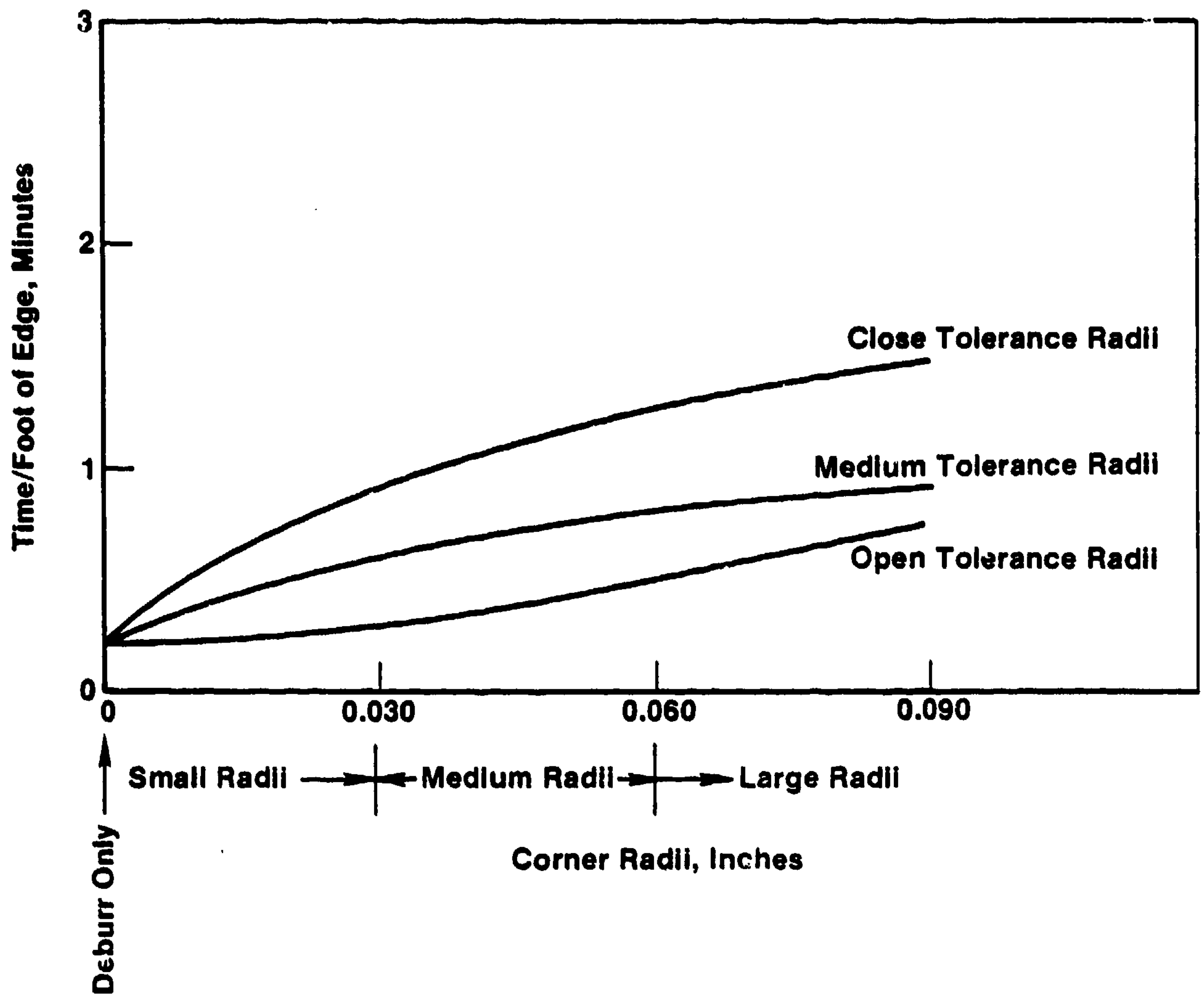
SMALL BURR: LESS THAN 0.004" HEIGHT



TIME REQUIRED TO HAND DEBURR AND EDGE BREAK

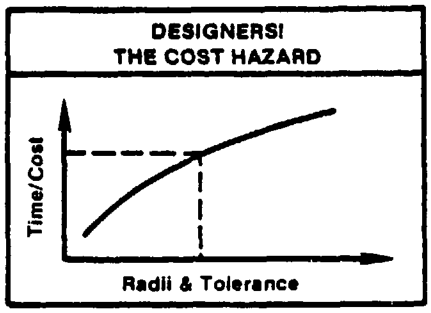


MEDIUM BURR: 0.004"-0.015" HEIGHT

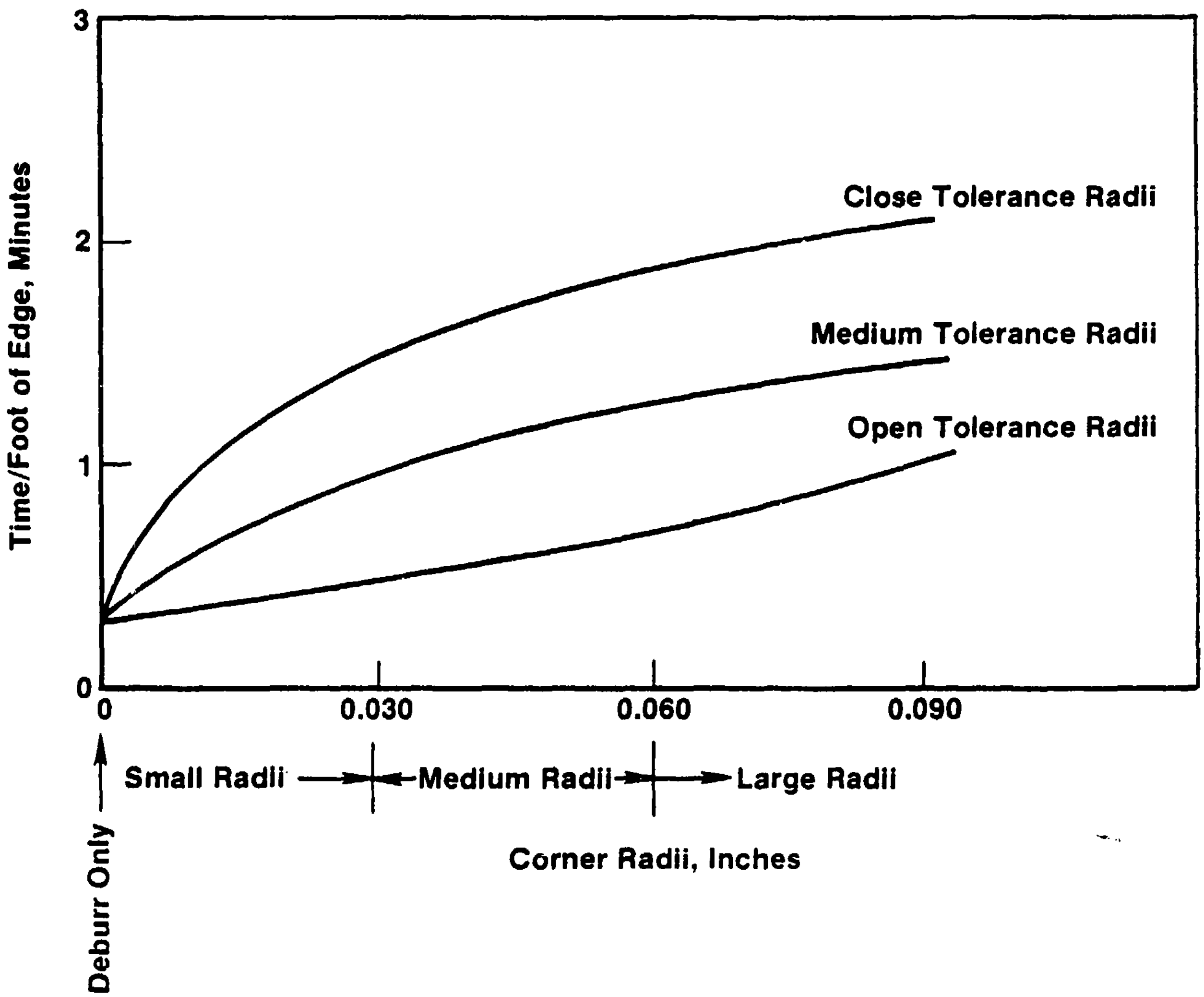


CED-M/C-XX

TIME REQUIRED TO HAND DEBURR AND EDGE BREAK

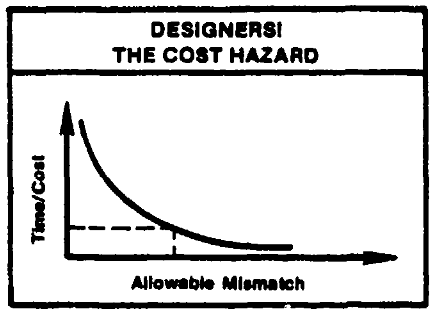


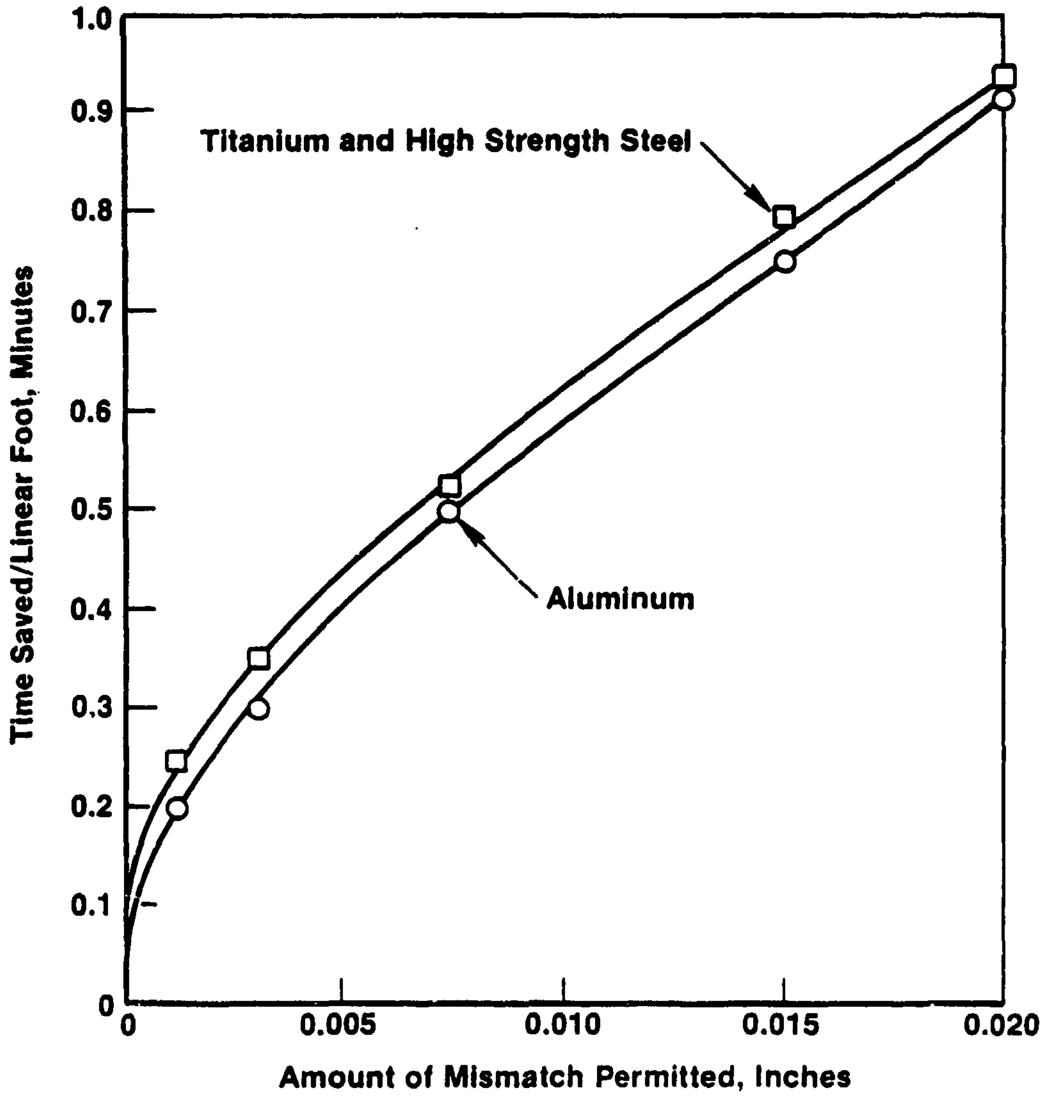
LARGE BURR: 0.015" AND ABOVE IN HEIGHT



CED-M/C-XXI

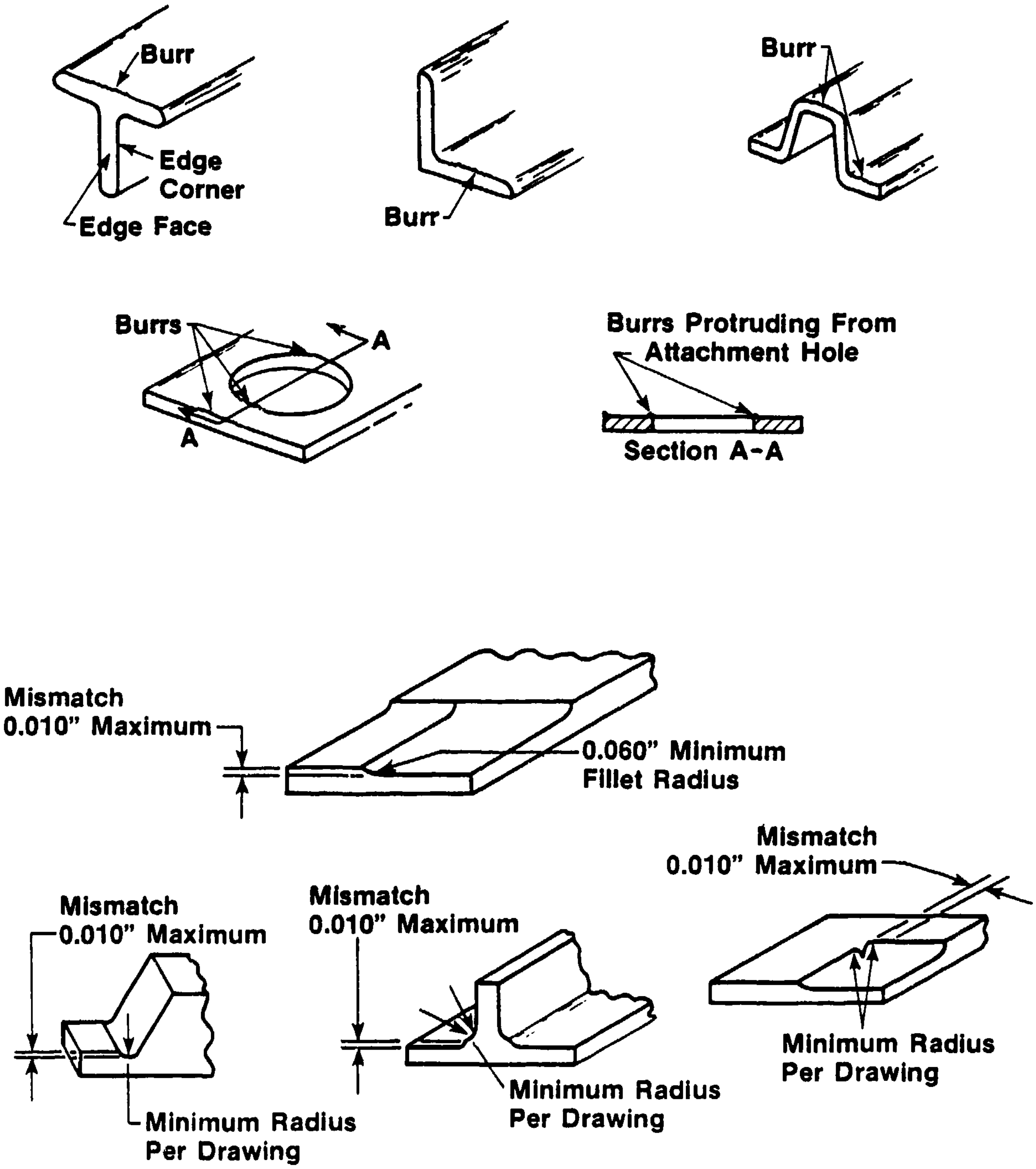
EFFECT OF MISMATCH





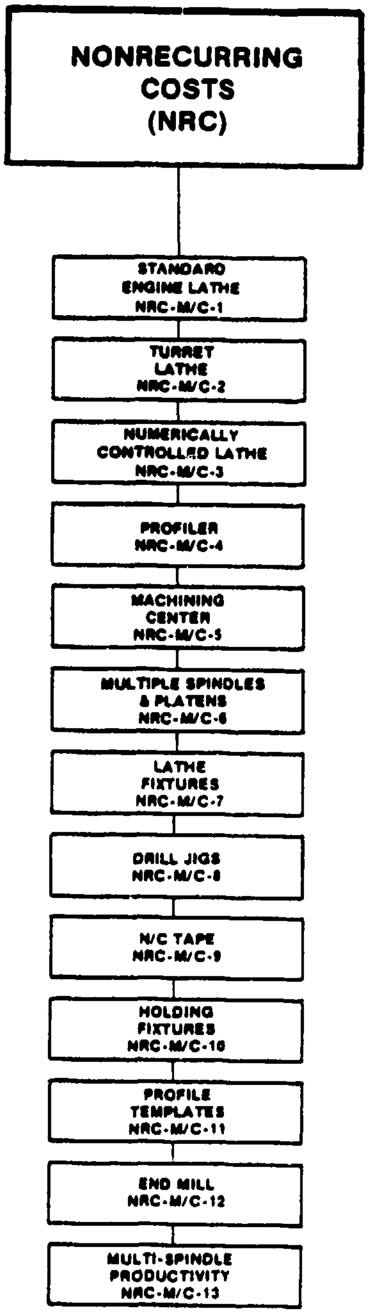
CED-M/C-XXII

TYPICAL EXAMPLES OF MISMATCH AND BURRS REQUIRING HAND FINISHINGS

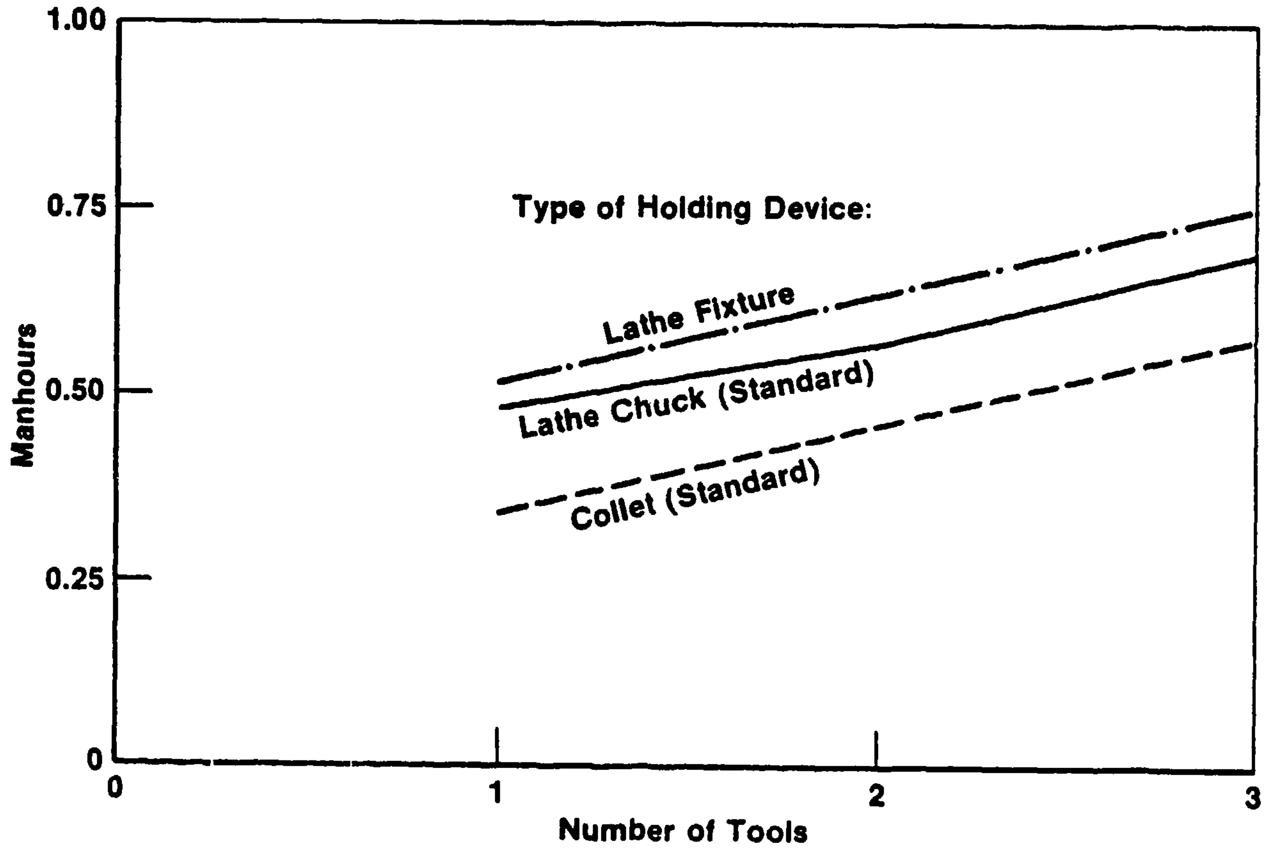


FORMAT SELECTION AID

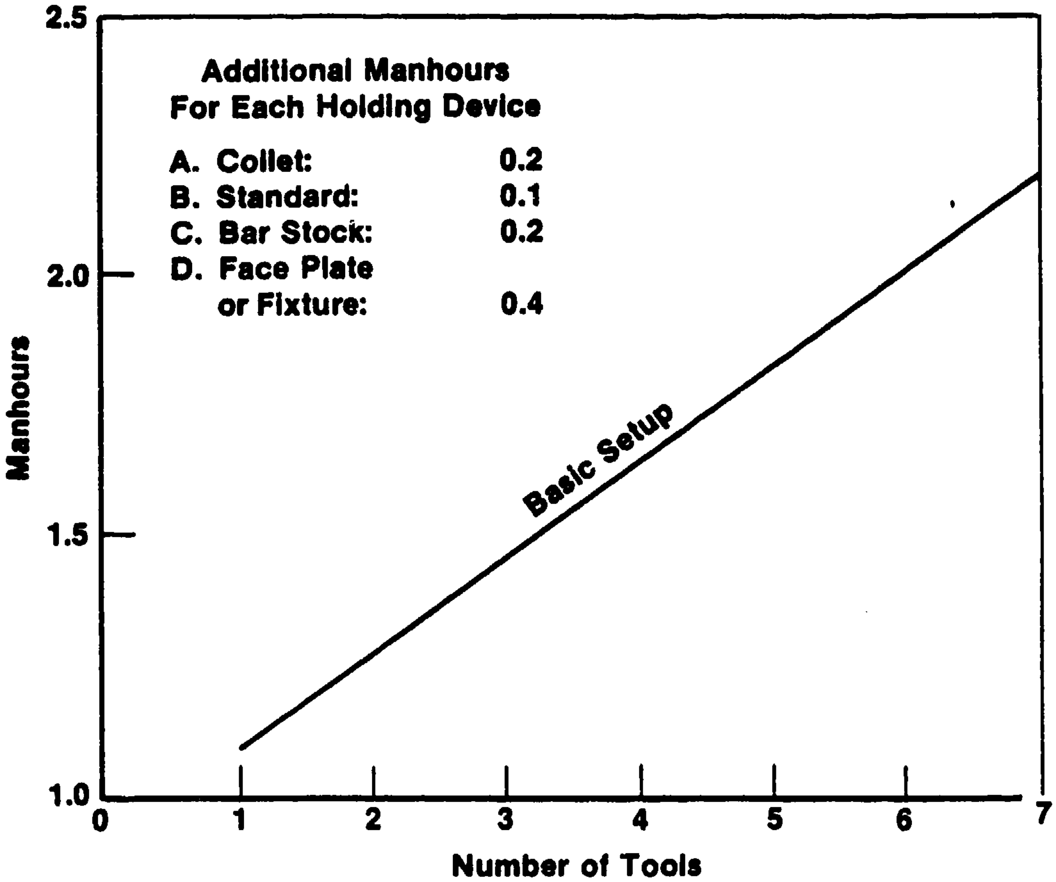
MACHINING OF METALS



SETUP TIME FOR STANDARD ENGINE LATHE

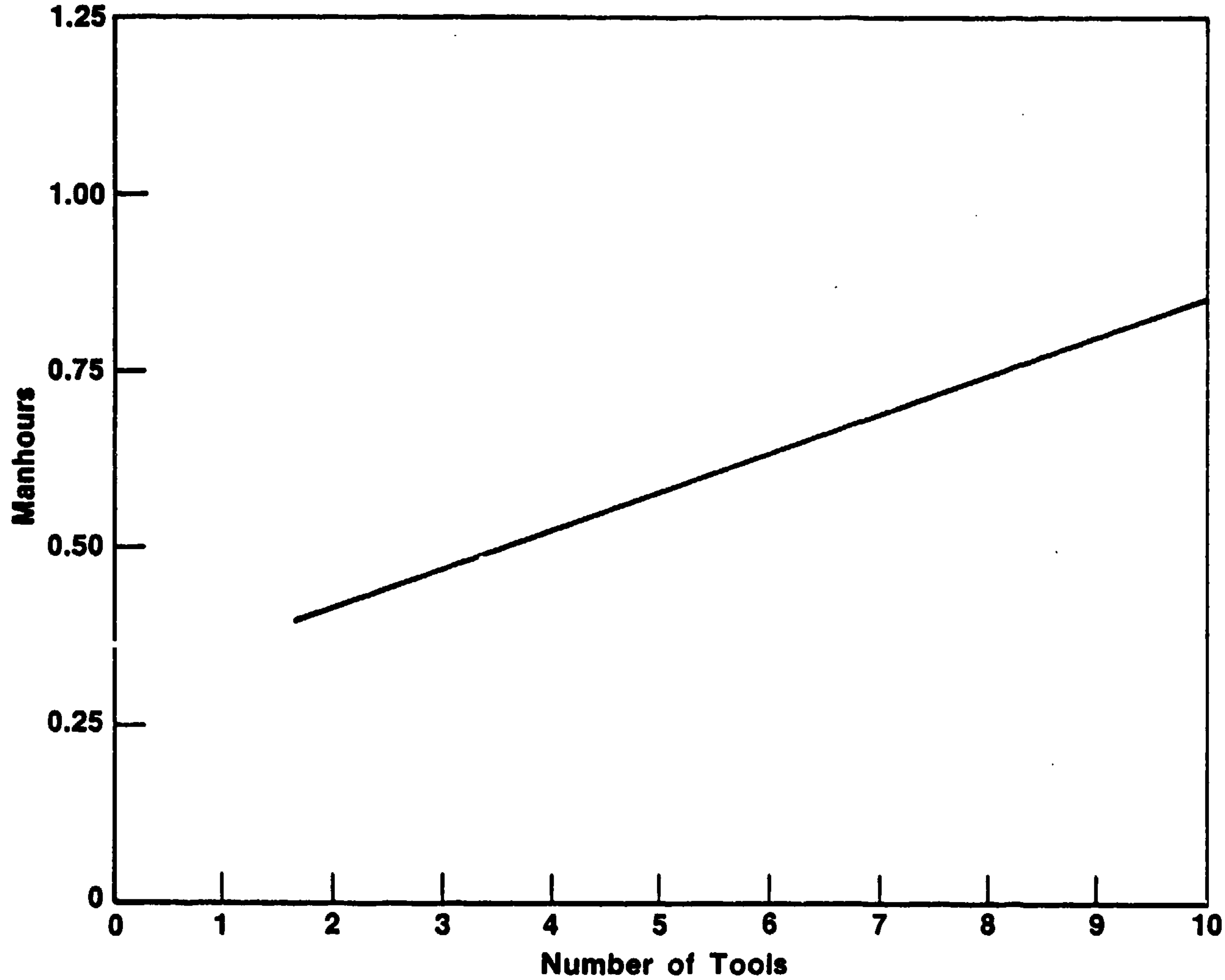


SETUP TIME FOR TURRET LATHE



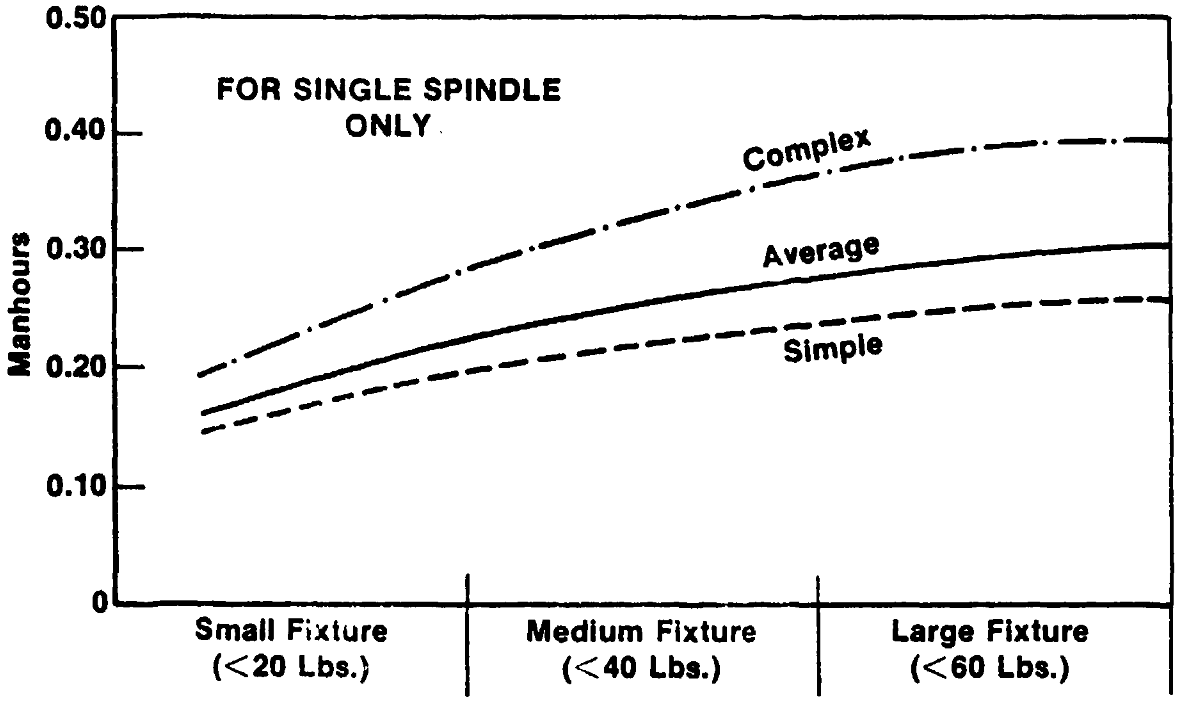
NRC-M/C-2

BASIC SETUP TIME FOR NUMERICALLY CONTROLLED LATHE



NRC-M/C-3

SETUP TIME FOR BED MILLING MACHINE, N/C OR TRACER CONTROLLED PROFILER



Note: For Fixtures Requiring Hoist Add 0.1 Manhour

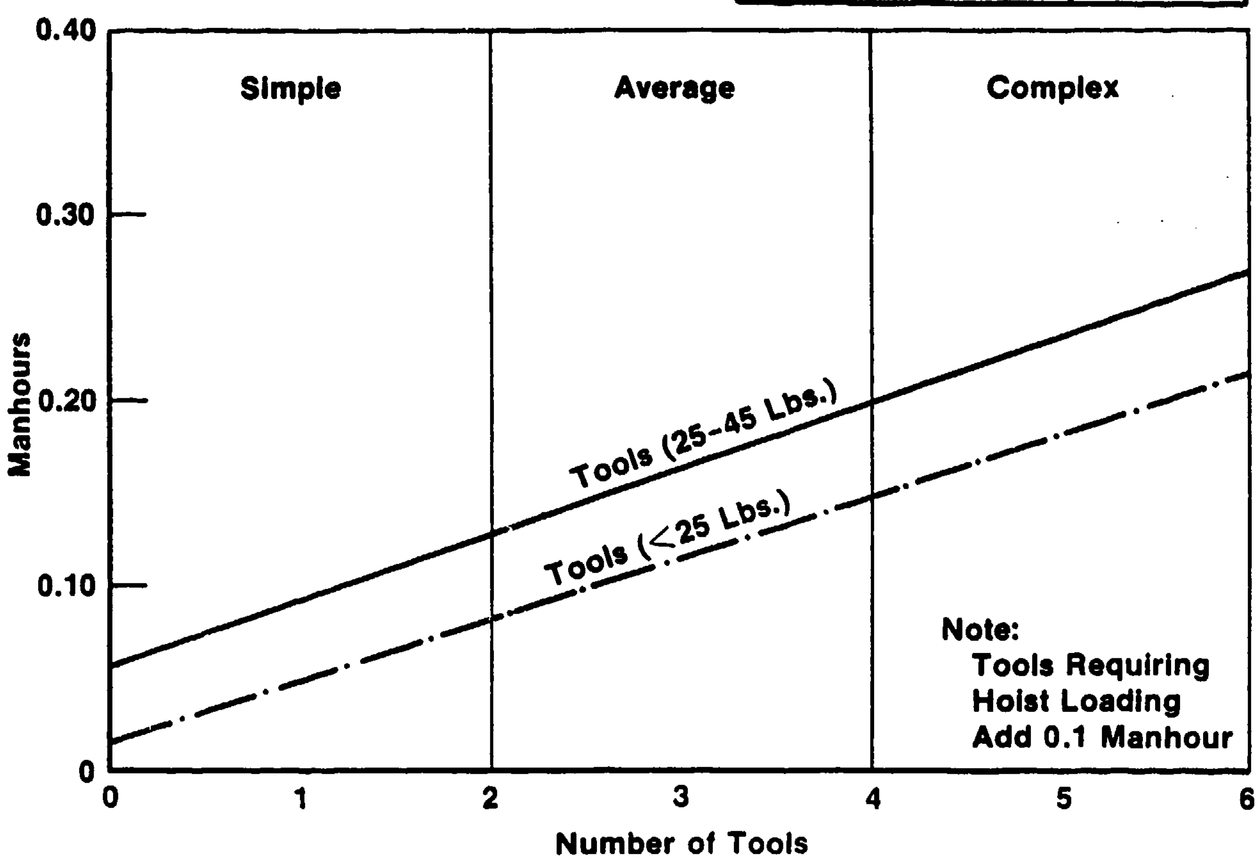
NRC-M/C-4

SETUP TIME FOR N/C OR CONVENTIONAL MACHINING CENTER

Additional Manhours For Loading Adapter

Type Of Cutting Tool	Manhours Per Tool
Drills	0.02
Reamers	0.04
Core/Spade Drill	0.04
Boring Tool	0.11
Tapes	0.04
Facing Tool	0.02
Presenting Tool	0.25
Loading Tool In Turret or Station	0.17/Tool

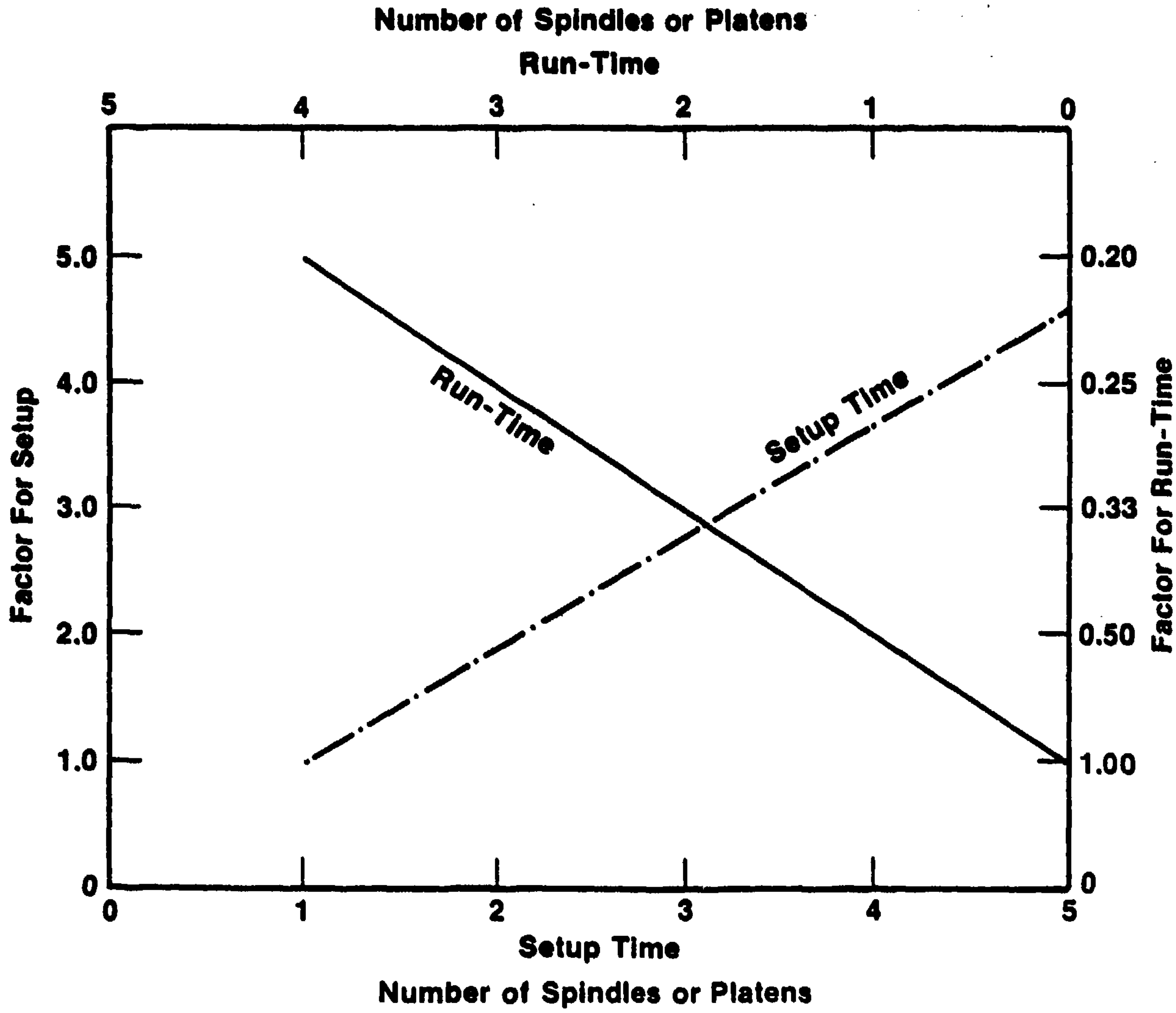
Fixture Only
Single Platen



Note: Setup Time = Fixture Time +
No. of Adapters Required +
No. Loaded In Turret

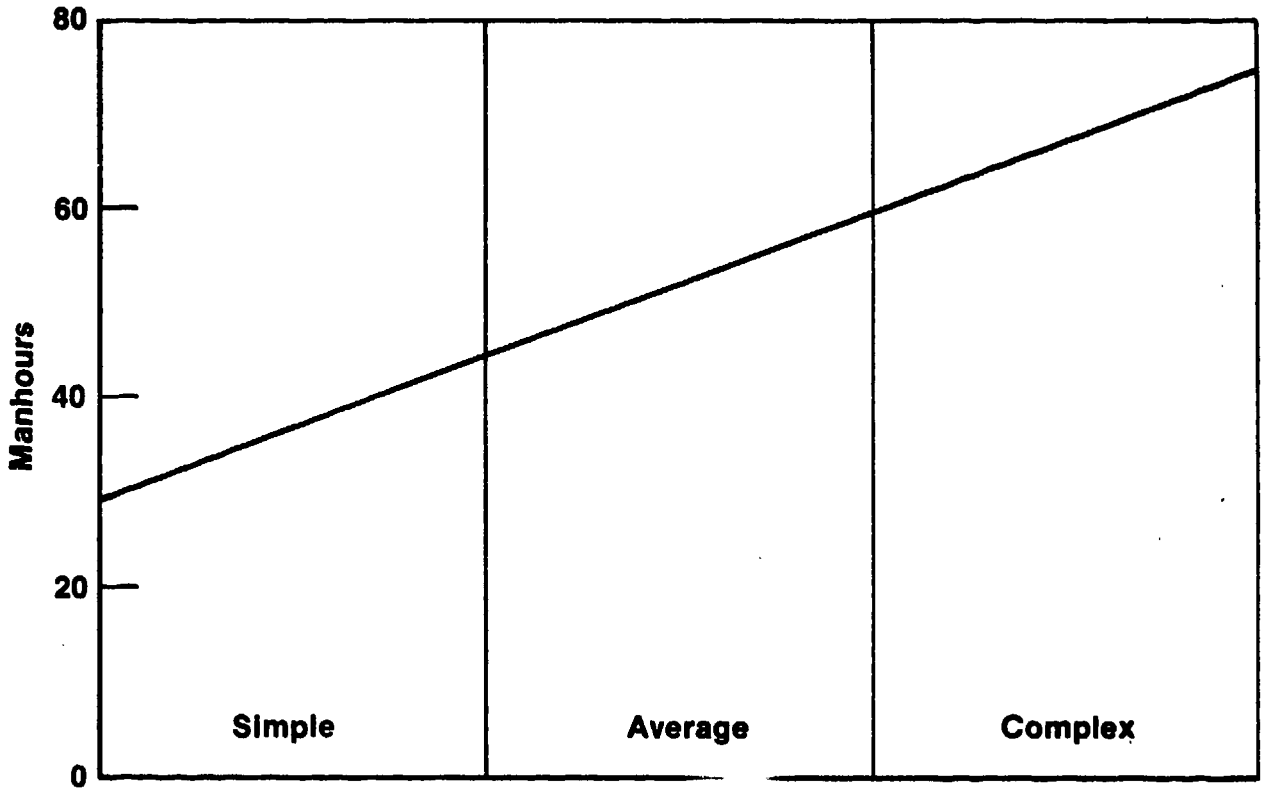
NRC-M/C-5

EFFECT OF MULTI-SPINDLES & PLATENS



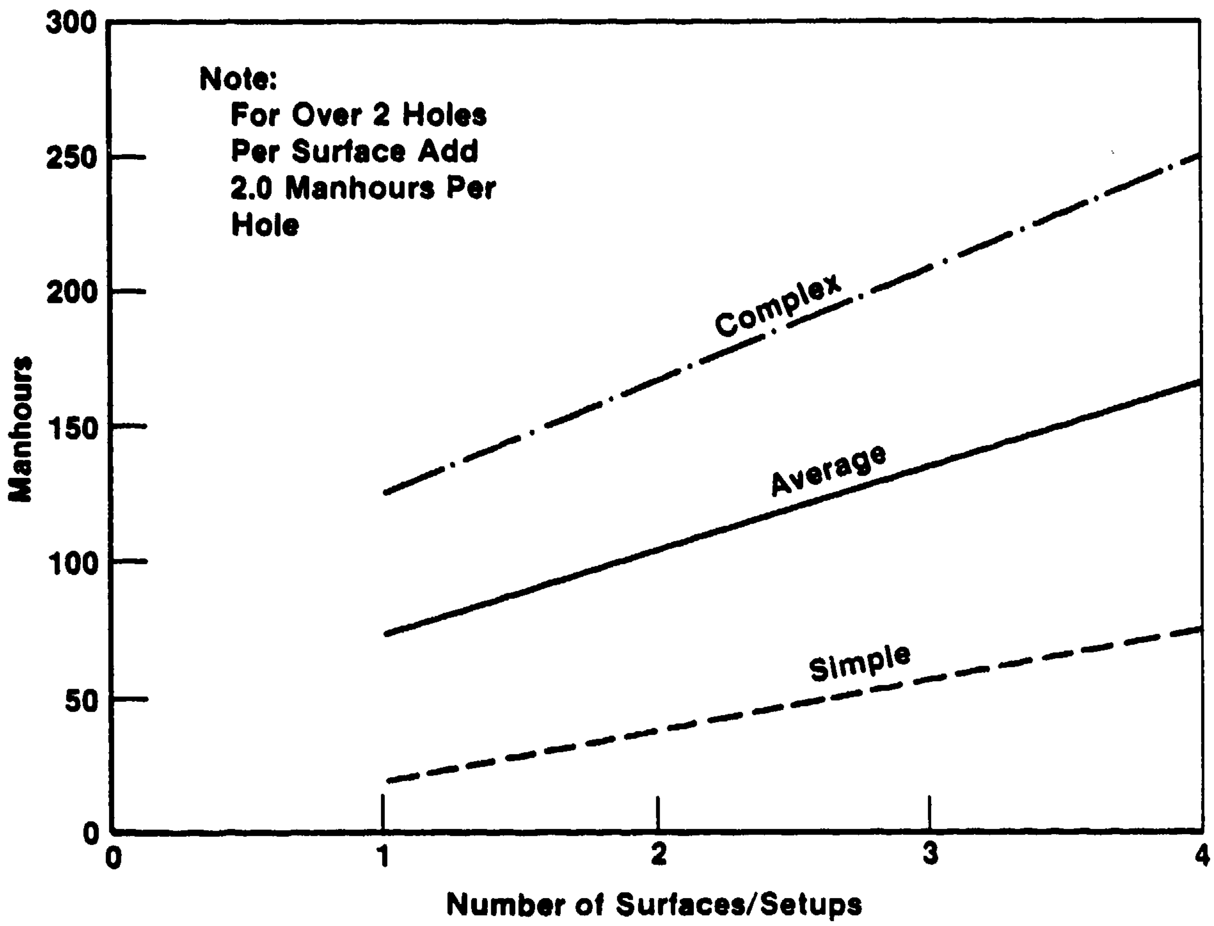
NRC-M/C-6

NONRECURRING TOOLING MANHOURS FOR LATHE FIXTURES (INCLUDES TOOL DESIGN & FABRICATION)

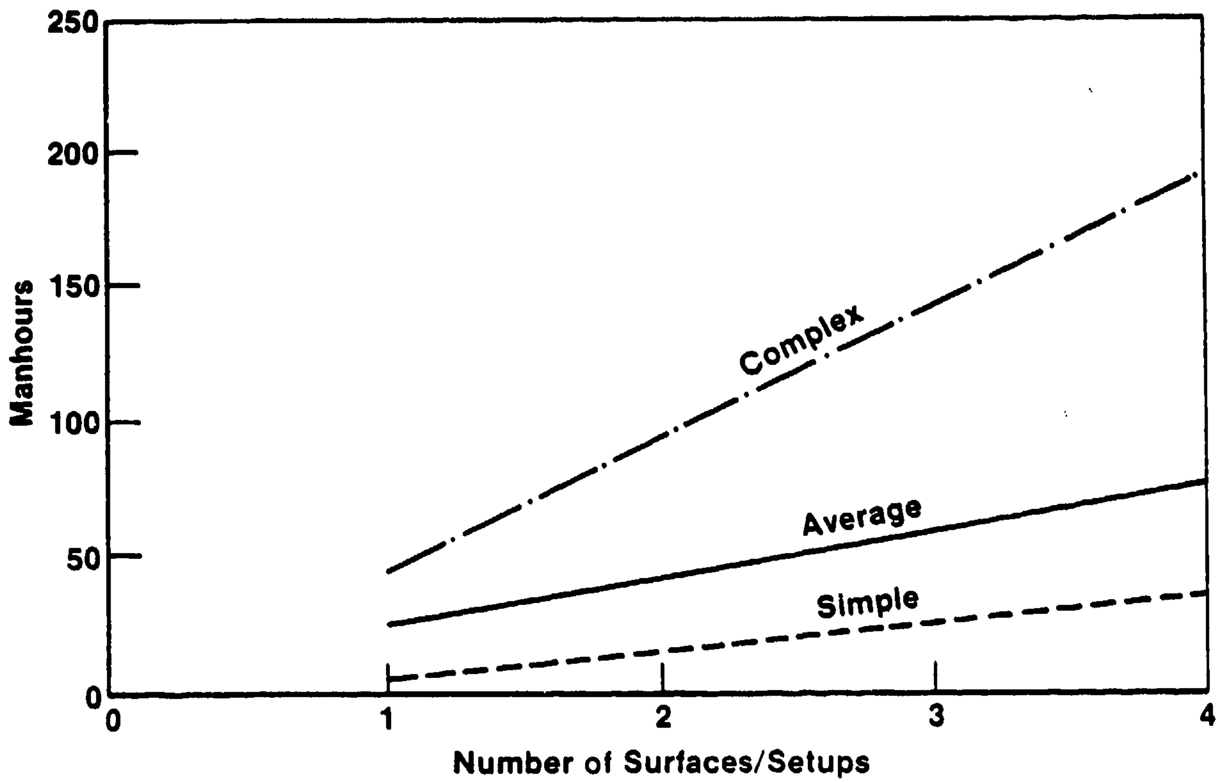


NRC-M/C-7

NONRECURRING TOOLING MANHOURS FOR DRILL JIGS/FIXTURES (INCLUDES TOOL DESIGN & FABRICATION)

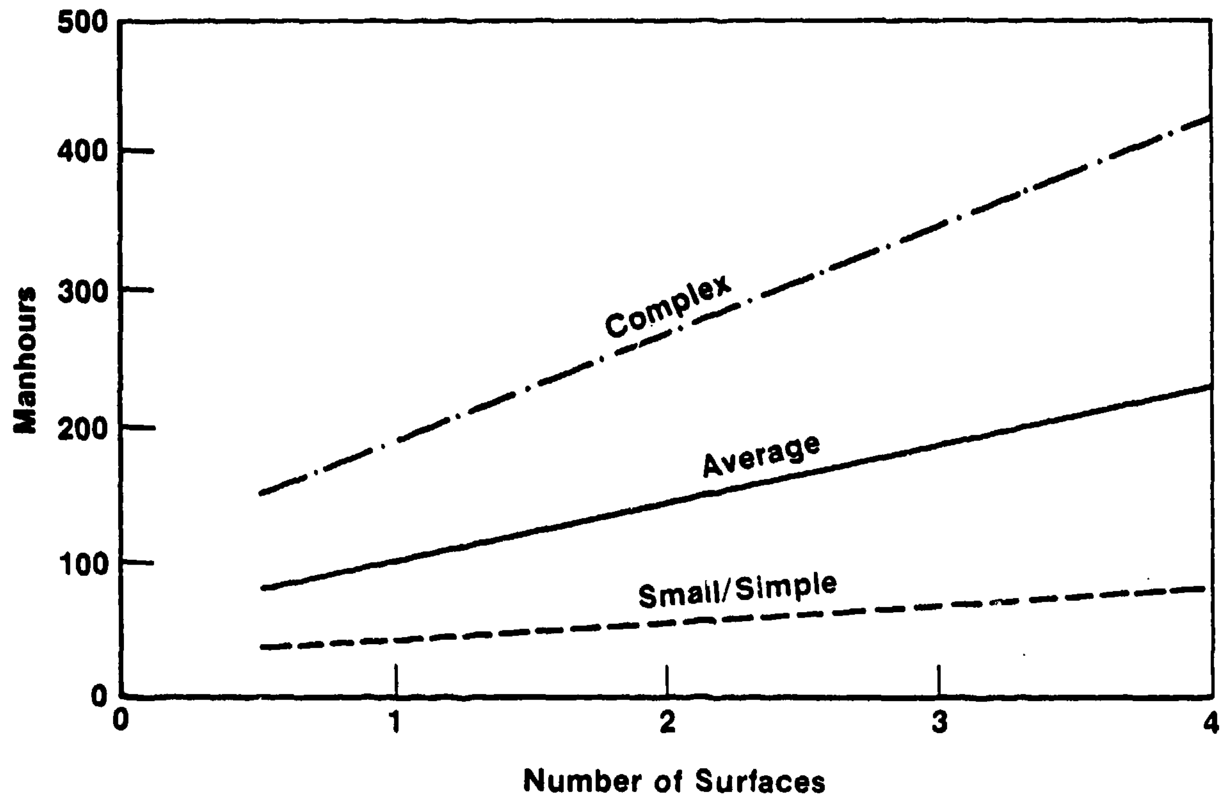


NONRECURRING TOOLING MANHOURS FOR N/C TAPE PREPARATION AND PROOFING



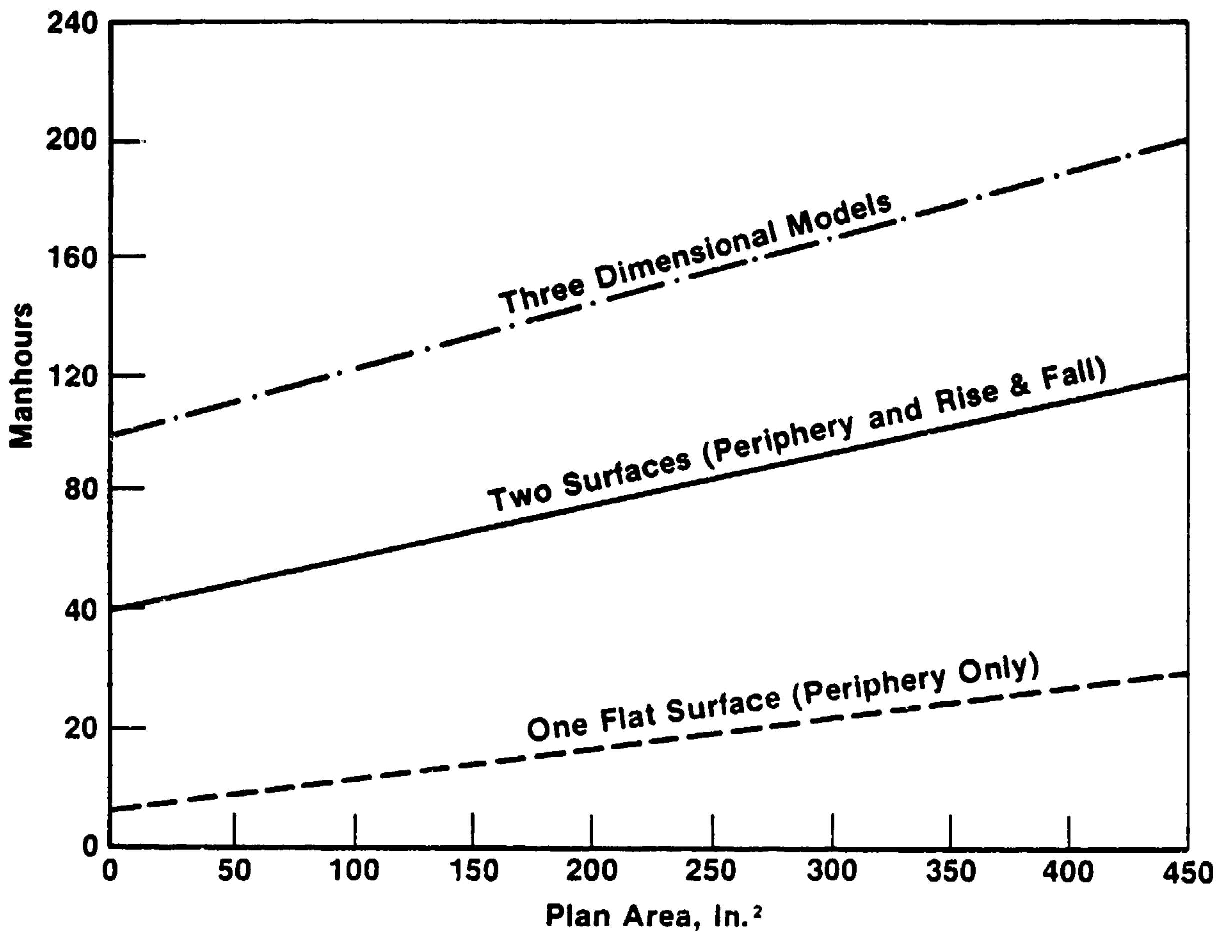
NRC-M/C-9

NONRECURRING TOOLING MANHOURS FOR MILLING & PROFILING HOLDING FIXTURES (INCLUDES DESIGN & FABRICATION)

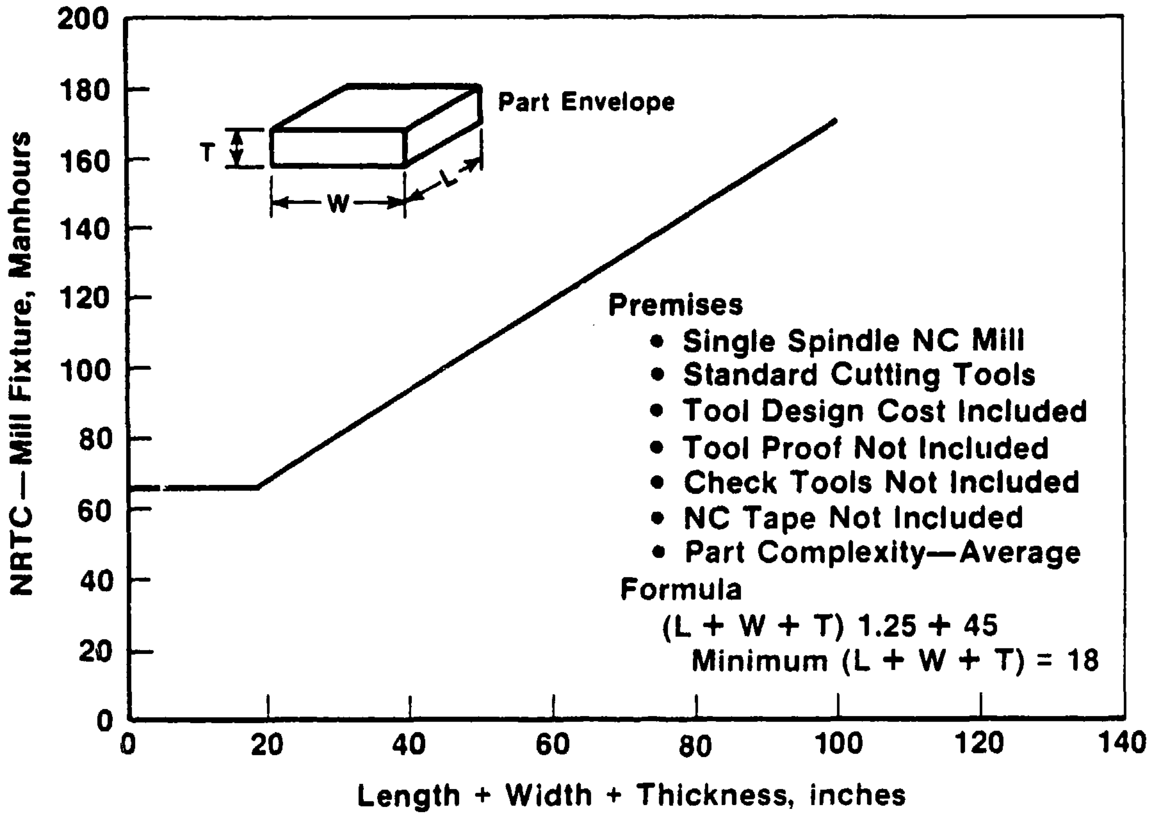


NRC-M/C-10

NONRECURRING TOOLING MANHOURS FOR PROFILE TEMPLATES/MODELS (TOOL DESIGN & FABRICATION)

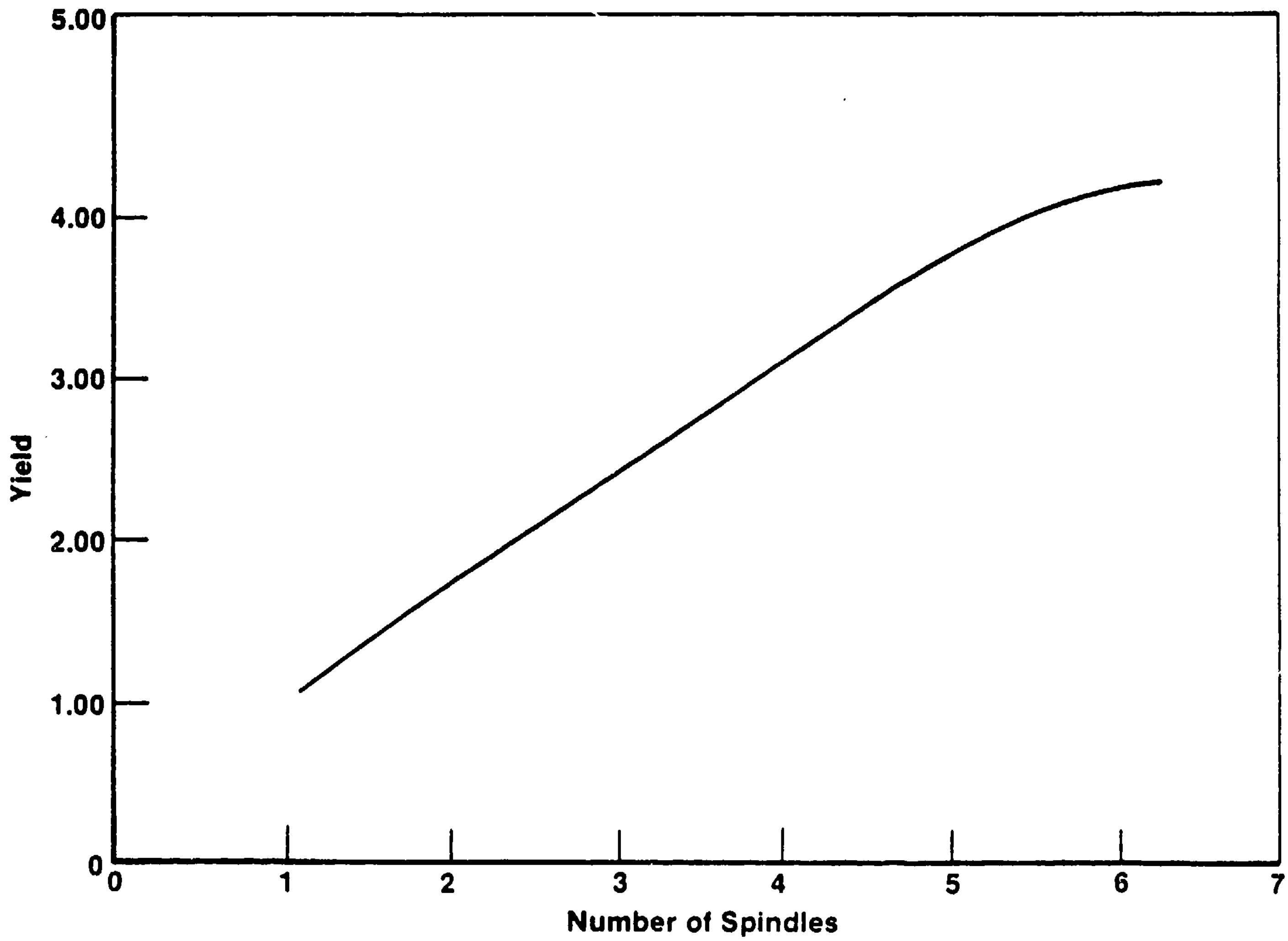


NONRECURRING TOOLING COST (NRTC) FOR END MILLING



Courtesy of Lockheed-California Company

PRODUCTIVITY INCREASE WITH MULTI-SPINDLES
(BASELINE: ALUMINUM)



NRC-M/C-13

4.10.9 Ground Rules for Machining

The following ground rules were chosen for developing data for the MC/DG machining section on aerospace discrete parts. Ground rules promote understanding and ensure consistency, uniformity, and accuracy in generating and integrating data into formats. The ground rules are in two categories; general and detailed.

4.10.9.1 General Ground Rules

Categories of general ground rules are:

(a) Machined Discrete Parts

(b) Materials

(c) Machining Processes

(d) Tooling

(e) Facilities and Equipment

(f) Data Generation - Machining Recurring Costs

(g) Data Generation - Machining Nonrecurring Costs

(h) Test, Inspection, and Evaluation (TI&E)

(i) Formats Required.

(a) Machined Discrete Parts

(1) Drawings of machined parts for the Air Force F-16, B-1B, and C-5B aircraft were studied to determine the commonality of cost-drivers. From this study, the pattern of cost-drivers was determined to enable dimensioned drawings to be prepared, showing configurations, materials, dimensions, holes, trim, etc.

(2) The machined discrete parts selected were representative of typical designer influenced cost elements (DICE) found on bulkheads, frames, spar caps, longerons, wing skins, and large and small miscellaneous machined parts. The DICE were therefore representative of structural parts common to both small and large aircraft.

(3) The machined discrete parts were selected to reflect a spectrum of machining processes (drilling, reaming, milling, profiling, etc.).

(4) Particular emphasis was placed on selecting parts to display a maximum number of cost-driver effects (CDE), including designer-influenced cost elements (DICE).

(b) Materials

(1) The alloys selected for the machined discrete parts, which represent those most commonly used in the airframe industry, were:

- Aluminum - 7075-T6/T73
- Titanium - 6Al-4V
- Steel - Due to the extensive hardness range of steels, and to indicate to airframe designers the effect of this characteristic, the machining cost has been presented as follows:
  - a) 4340 in normalized condition, and,
  - b) Average values for:
    4340 (180-200 ksi condition)
    HP 9420 Q&T (220-240 ksi)
    HP 9430 Q&T (220-240 ksi)
    4330V Q&T (220-240 ksi)
    300M Q&T (280-300 ksi).

Metal removal rates for a number of specific aluminum, titanium, and steel alloys are presented using CDE formats.

(c) Machining Processes

(1) Incorporation of the selected DICE requires a range of manufacturing processes such as:

- Milling
  - End Milling
  - Slab milling
  - Profiling
  - Face milling
  - Pocket milling
  - Gang milling
- Turning
- Boring
- Broaching
- Threading
- Drilling
- Spotfacing

- Grinding
- Countersinking
- Counterboring
- Reaming
- Lapping
- Honing.

(2) Unconventional methods of metal removal were not considered.

(3) Heat treatment/processing - Conventional heat treatment process costs, such as those for solution, aging, and furnace treatments, were not included.

(4) Post machining processes, such as heat-treatment, anodizing, and alodining, were not included.

(d) Tooling

(1) Conventional aerospace tooling was considered in developing guidelines for nonrecurring cost. Examples of nonrecurring tooling are:

- Drill fixtures
- Mill fixtures
- Holding fixtures
- Lathe fixtures
- Vacuum chucks
- N/C tape preparation and try out.

(2) Perishable tooling (special form cutters, drills, standard mill cutters, taps, reamers, etc.) were not considered.

(e) Facilities and Equipment

(1) Adaptive controls and DNC/CNC equipment were not included.

(2) Both conventional and N/C machine tools were, however, considered.

(3) The parts studied reflected a range of machine tool requirements and those representative of typical aerospace manufacturing are:

- Milling
  - Horizontal and vertical (conventional or N/C)

- Profiling (N/C versus model tracing)
  - Vertical/horizontal - 3 axis, 5 axis
  - Spar mill - 3 axis
  - Skin mill - 3 axis
- Turning/boring (conventional or N/C)
  - Engine lathe
  - Turret lathe
  - Vertical lathe
- Drill press (conventional or N/C)
- Broaching machine.

(f) Data Generation - Machining Recurring Costs

(1) Recurring standard man-hour data were generated for each of the selected machined parts.

(2) Operation sheets describing, in detail and sequence, each machining operation, including the necessary tooling, were prepared and used as the basis for establishing both the standard recurring man-hours and the nonrecurring man-hours. The type of machine (number of spindles, N/C, conventional, etc.) and type of cutting tool (high-speed steel, carbide) were specified.

(3) With machined parts, there is no base part as with, for example, sheet metal. Machining is a process and each discrete part constitutes a series of DICE created in a plate, bar, forging, etc. The machining section is therefore different and more complex than the other MC/DG sections developed.

(4) DICE elements, as applicable, are treated as separate cost elements.

(5) Instructions are provided in the MC/DG User's Manual (UM 450261000, Volumes 1, 2, and 3) to enable designers to convert the manufacturing man-hours provided for various design quantities.

(6) All cost data were presented in man-hours or as relative values.

(7) Recurring costs for tool maintenance, planning support, etc., were not included.

(8) The comparative cost of materials (aluminum, steel, titanium) and the base stock (plate, forging, casting, etc.) were not included. As in the case of other MC/DG sections, each user incorporates company material costs on the MC/DG designer worksheet.

(9) For proprietary reasons, business sensitive information provided by contributing companies is not presented in the MC/DG.

(g) Data Generation - Machining Nonrecurring Costs

(1) In general, the nonrecurring cost includes the cost of all contract type tooling, both the tool design, and tool manufacturing time plus the cost of preparation and proofing of N/C tapes. (Ref. (d) - Tooling).

(2) The type of tooling used for each part was listed on operation sheets.

(h) Test, Inspection, and Evaluation (TI&E)

The man-hours for test, inspection, and evaluation (TI&E) of machined parts are presented to designers in Section 4.7.6 of MC/DG User's Manual, UM 450261000, Volume 3.

(i) Formats Required

(1) The methodology developed, reviewed, evaluated, and approved by design engineers in previous sections of the MC/DG was utilized for evolving the formats for machining. These formats are:

- Cost-driver effects (CDE)
- Cost-estimating data (CED)
- Designer-influenced cost elements (DICE).

4.10.9.2 Detailed Ground Rules

The following detailed ground rules were developed:

(1) Standard mismatch was allowed.

(2) Standard dimensional tolerance practice was acceptable.

(3) Cutting feeds, speeds, depth-of-cut, etc., were based on the contributing company's practice.

(4) The discrete part tolerances, which were considered standard, were:

0.0 + 0.060 in.
0.00 + 0.030 in.
0.000 + 0.010 in.
0.0000 + 0.0005 in.*
Angular 0° 30'
Surface texture - 125 micro-inch for aluminum;
160 micro-inch for titanium and steel.

(5) A production, in contrast to a prototype environment, was assumed for machined discrete parts.

(6) DICE factors for secondary operations include:

- Special texture finishes
- Broaching
- Honing
- Close tolerances
- Reaming
- Lapping
- Keyways
- Boring
- Threading/tapping.

(7) DICE factors also include:

- Milling or profiling operations requiring special form cutters
- Profiling operations requiring small cutters (under 0.375 in. dia.)
- Profiling operations requiring thin webs or pockets (less than 0.125 in.).

*Ream/bore/grinding only - Closer tolerances than those specified above were considered as DICE.

4.10.10 Definitions

The MC/DG classifies parts for which relative costs and manufacturing man-hours are being presented as simple, average, or complex. Such definitions are useful for cost-driver effect (CDE) formats. Examples of such classifications for parts, and those produced with conventional milling machines and machining centers are:

Machined Parts

- Simple Part: A part that has straight lines, sides, etc., and can be completely machined in one setup on a standard conventional machine.

- Average Part: A part, such as a channel or "T", with 90° and/or 180° surfaces, which can be completely machined in one setup on a machine with either vertical or horizontal axes, or both, requiring a maximum of two setups.

- Complex Part: A part with contoured sections, cut-outs, pockets, or thin sections that requires a machine with a tilting arbor or spindle, i.e., a minimum of three axes requiring two or more setups.

- Exotic Part: A part with any or all of the above features, plus compound and/or swarf cuts, deep and long pockets with small corner radii undercuts that complicate metal removal, etc., and that requires over three setups and a machine with over three axes.

Conventional Milling Machine

- Simple Part: A part that can be completed (except for heat-treatment and processing) in one milling machine (or profiler) setup, utilizing a maximum of two standard milling cutters (either end-mills or circular) with no angular cuts or additional operations, such as drilling and grinding, required. No designer-influenced cost elements (DICE) are required in the part to achieve the intended function and the part can be completely fabricated on a standard conventional machine.

- Average Part: A part that can be completed (except for heat-treatment and processing) in a maximum of three setups on the same machine with a maximum of four standard mill cutters, plus a limited number of additional operations (three or less), such as drilling and grinding, on other than the primary machine. This average part will have a maximum of three DICE elements and can be completely fabricated on a multiple axis machine.

- Complex Part: Any part not complying with the above definitions and that may require a machine with multiple axes and also additional setup capabilities.

Machining Centers

- Simple Part: A part that can be completed (except for heat-treatment and processing) utilizing a single pallet, one setup, with a maximum of six tools in the turret and with no additional operations required on any other machine.

- Average Part: A part that can be completed (except for heat-treatment and processing) utilizing both pallets of the machine with two setups per pallet, and a maximum of 15 tools in the turret with a maximum of three operations and setups required on other machines.

- Complex Part: Any part suitable for manufacture on a machining center, but not complying with the above definitions.

4.10.11 Supplementary Forms

4.10.11.1 Worksheets for Designer Use

To conveniently utilize the manufacturing man-hour data presented in the MC/DG, Designer Worksheets have been prepared. These have also been utilized for various examples for discrete parts and sub-assemblies in the MC/DG sections and also for the integrated examples on aluminum, titanium, and composite fuselage panels (Volume III of the User's Manual UM 450261000).

While the use of the Designer Worksheets is optional, a blank copy is included for the convenience of those that prefer this approach and would like to reproduce a supply. The worksheet is:

- Machining Cost Worksheet.

4.10.11.2 Document Request Order Form

The documents available on the Air Force ICAM "Manufacturing Cost/ Design Guide" project are listed on the Request Order Form provided at the conclusion of this section. Documents generated under the contract contain controlled distribution and export control clauses.

SECTION 5.0
REFERENCE DOCUMENTS

5.1 Applicable Documents

Item	Description
1	Integrated Computer Aided Manufcturing (ICAM) "Manufacturing Cost/Design Guide" (MC/DG) Interim Technical Reports for Period: a. 28 September 1979 - 29 February 1980, ITR450260002U b. 28 September 1979 - 16 May 1980, ITR450260002U c. 17 May 1980 - 17 August 1980, ITR450260003U d. 18 August 1980 - 31 October 1980, ITR450260004U e. 1 November 1980 - 31 January 1981, ITR450260005U f. 2 February 1981 - 30 April 1981, ITR450260006U g. 4 May 1981 - 31 July 1981, ITR450260007U h. 3 August 1981 - 30 October 1981, ITR450260008U i. 2 November 1981 - 29 January 1982, ITR450260009U j. 1 February 1982 - 30 April 1982, ITR4502600010U k. 1 September 1983 - 30 November 1983, ITR450260011U l. 1 December 1983 - 29 February 1984, ITR450260012U m. 1 June 1984 - 31 August 1984, ITR450260013U
2	MC/DG User's Manual for Airframes, AFWAL-TR-83-4033 (Volumes I, II, III & V).
3	MC/DG User's Manual for Electronics, AFWAL-TR-83-4033 (Volume IV).
4	Project Summary, E0 450260000 (Volume VI).
5	Technology Transfer Summary, TTD450260000 (Volume VII).
6	Noton, B.R., Claydon, C.R., Larson, M., "ICAM Manufacturing Cost/Design Guide", Materials Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio. Technical Report AFWAL-TR-80-4115, September 1977 - July 1979 a. Volume I: Demonstration Sections b. Volume II: Appendices to Demonstration Sections c. Volume III: Computerization.
7	Summary of Air Force/Industry Manufacturing Cost Reduction Study, Materials Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio. Technical Report No. AFML-TM-LT-73-1, January 1973.
8	Summary Report on the Low Cost Manufacturing/Design Seminar, Materials Laboratory, Air Force Wright Aeronautical Labora-

tories, Wright-Patterson Air Force Base, Ohio. Technical Report No. AFML-TM-LT-74-3, 15 December 1973.

9 Aerospace Cost Savings - Implications for NASA and the Industry, National Materials Advisory Board, National Academy of Sciences, Report No. NMAB-328, 1975.

10 Noton, B.R., et al, "Manufacturing Cost/Design Guide", Materials Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio. Technical Report No. AFML-TR-76-227, December 1976.

11 "Manual for Panel Chairmen and Working Groups", Department of Defense/Industry Metal Chip Removal Conference, p. 16, 8-10 February 1977, Daytona Beach, Florida.

12 "Science Base for Materials Processing--Selected Topics", National Materials Advisory Board, Publication No. NMAB-355, 1979.

13 "Machining Data Handbook", 3rd Edition, Vol. 1 and 2, Machinability Data Center, Metcut Research Associates, Inc.

14 "Forging Design Handbook", Copyright 1972, American Society for Metals. Sponsored by the United States Air Force.

15 Gillespie, LaRoux K., "Deburring Technology for Improved Manufacturing", Society of Manufacturing Engineers, 1981.

16 Trucks, H. E., "Designing for Economical Production", Society of Manufacturing Engineers, 1974.

17 Mark's, "Mechanical Engineers' Handbook", Sixth Edition, McGraw-Hill Book Company.

18 Linsley, Horace E., "Broaching Tooling and Practice", The Industrial Press, 1961.

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MACHINING COST WORKSHEET

	Machining Features (DICE)	Format No.	Machining Run-Time (Hours) I.	Setup Time (Hours) II.	Nonrecurring (Hours) III.
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
Machining Manhours/Part					
Machining Manhours for Design Quantity					
Labor Rate ($/Hour)					
Machining Cost for Design Quantity					
Total Cost (I + II + III)					

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DOCUMENT REQUEST ORDER FORM

SUBMIT DOCUMENT REQUESTS TO: **Bryan R. Noton**
Battelle Memorial Institute
505 King Avenue, Columbus, Ohio 43201-2693

WITH COPY TO: **AFWAL/MLTC**
CIM Program Library
Wright-Patterson AFB, OH 45433

VOLUME NUMBER AND MANAGEMENT NUMBER	TITLE OF DOCUMENT	INDICATE (✓) DOCUMENT REQUESTED
VOLUME I (UM 450261000)	Airframe User's Manual	
VOLUME II (UM 450261000)	Airframe User's Manual	
VOLUME III (UM 450261000)	Airframe User's Manual	
VOLUME I (UM 450262000)	Electronic Design User's Manual	
EO 450260000 Volume VI	Project Summary	
TTD450260000 VOLUME VII	Technology Transfer Summary	

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Document(s) requested for the purpose of (intended use and program/project application must be provided):

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